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16. ABSTRACT The report summarizes the initial loading of data into the Fine Particle Emissions Information System (FPEIS), a computerized database on primary fine particle emissions to the atmosphere from stationary sources, designed to assist engineers and scientists engaged in fine particle control technology development. The FPEIS will contain source test data including particle size distributions; chemical, physical, and bioassay testing results performed on particulate samples; design and typical operating data on particle control systems applied; process descriptions of the sources; and descriptions of the sampling equipment and techniques employed. The FPEIS, a successor to the MRI Fine Particle Inventory developed in 1971, report summarizes 52 series of tests on 33 types of sources and a variety of conventional and novel control devices. The test series contain over 700 test runs or sampling events, utilizing impactors of various types, optical particle counters, and diffusion batteries for the fine particle measurements. Particle size distributions from typical tests are given. The report also describes the FPEIS, summarizes the data acquisition activities, and assesses data acquired relative to the effectiveness of particle control technology and the current state of the FPEIS database. The report discusses particulate sampling and sizing techniques, and particulate-related health effects.

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FINE PARTICLE EMISSIONS INFORMATION SYSTEM: SUMMARY REPORT (SUMMER 1976)

by

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Contract No. 68-02-1324, Task 42
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Research Triangle Park, NC 27711

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PREFACE

This report was prepared for EPA/IERL-RTP under contract No. 68-02-1324, Task 42, and was monitored by Mr. Gary L. Johnson of the EPA.

The work was performed in the Physical Sciences Division of Midwest Research Institute. Mr. M. P. Schrag, Head, Environmental Systems Section, served as the project leader.

The report was written by Dr. A. K. Rao with assistance from Mr. Schrag and Dr. L. J. Shannon. Mr. J. Shum, Assistant Environmental Engineer, Environmental Systems Section, contributed significantly to this program.

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October 8, 1976

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SUMMARY

The Fine Particulate Emissions Information System (FPEIS) was developed for the Industrial Environmental Research Laboratory-RTP, Environmental Protection Agency under Tasks Nos. 25, 36, 37, and 42 of Contract No. 68-02-1324. The FPEIS is a computerized data base which is designed to contain all currently available fine particle source test measurements and control device evaluations. FPEIS contains particulate source characteristics, control device(s) parameters, test details, particulate physical, biological and chemical properties, and particle size distribution data. By providing a uniform compilation of fine particle information and data, the FPEIS can serve the needs and interests of a broad spectrum of users. These users include plant officials, control device manufacturers, measurement equipment/method developers, government officials responsible for the development of fine particulate control strategies, and other researchers.

The FPEIS data base has been created through the use of SYSTEM 2000, a flexible, computerized data base management system. SYSTEM 2000 was developed by MRI Systems Corporation (no relation to Midwest Research Institute) of Austin, Texas, and offers unique file management features and flexibility. The data base computerization aspect of the FPEIS has been provided for EPA by MRI Systems Corporation under a separate contract.

The FPEIS data base development consisted of seven steps:

1. Establishing information requirements.

2. Data acquisition.

3. Data element definition.

4. Development of input and output formats.

5. Preparation of a trial data base for MRI Systems Corporation.

6. Screening, reducing, coding, keypunching, and editing the data obtained.

7. Analyzing and evaluating the data.

Following preliminary evaluation, the data base was implemented on the UNIVAC 1110 computer at EPA's National Computer Center at Research Triangle Park, North Carolina, and MRI Systems Corporation performed a variety of tests on the data base using the trial data. In addition to this report, there are available an extensive FPEIS Reference Manual (EPA-600/2-76-173, June 1976) and a comprehensive FPEIS User Guide (EPA-600/2-76-172, June 1976). A FPEIS User's Workshop was held in June 1976 to acquaint potential users with the system. Under a new task of the above mentioned contract, work is under way to update the system with new data.

A variety of techniques were utilized in collecting the fine particle source test data, including a systematic search of the technical literature, personal contacts with EPA project officers, EPA and other government contractors, university and industry sources, followed by telephone and written requests when advisable. An initial group of 27 reports and papers was selected from which source/collector measurement data were extracted for entry into the system. These data were used for the initial data base loading, because they collectively included nearly all of the data elements in the data base. As such, they could be of assistance in verifying the data base construction.

The FPEIS organization consists of test series, test subseries, and test run levels. A test run, which is the fundamental element of the FPEIS system, is defined as "any test measurement of a specific source/control device combination for a specific length of time, with specific particle size measuring equipment/method." The test subseries, consisting of one or more runs, describes the particle-laden gas stream at the inlet or outlet of the control device(s). The data elements of a test subseries include source and control device operating parameters, test specifics including sampling method and physical, biological, and chemical properties of the particulates, particulate measurement method, and size distribution data. A test series consists of one or more test subseries and represents all the information pertaining to the source/collector combination that was tested.

Input to the system is prepared by completing six data input forms. Form No. 1 includes a source description and test series particulars. Form No. 2 provides entries for control device(s) design parameters. Forms Nos. 3 and 4 are for test particulars, control device(s) operating parameters, mass train test results, and particulate physical properties. Form No. 5 is used for particulate bioassay and chemical composition test results. Form No. 6 is for measurement instrument/method description and particle size distribution data.

The user of SYSTEM 2000 can receive a variety of information as output; however, the standard output format includes a table containing source, control device(s), test and particulate descriptions, particle size distribution data, and a plot of mass, surface, and number size distributions for each run.

At present, the FPEIS data base consists of 717 test runs for 33 different source/collector combinations. All of the data were obtained on controlled sources. Furthermore, almost all of the size distribution data were obtained with inertial impactors. These size measuring devices have some inherent deficiencies which bear upon the quality of these data. The data, classified according to source type and control device type, are shown in Table 6. For these data, the average inlet and outlet mass concentrations and overall control device efficiency are shown in Table 7. Inadequacies in many of the test methods severely restrict the accuracy and comprehensiveness of the data base.

SECTION 1

INTRODUCTION

Increased awareness of the importance of fine particulate pollution has fostered discussion regarding programs and alternatives for controlling fine particle emissions from industrial sources. Formulation and implementation of control strategies for minimizing fine particulate emissions require adequate information on emissions. Such necessary information includes sources of fine particulate, effectiveness of control equipment, process operating parameters for source and equipment combinations, and the quantities of fine particulate emitted, with characterization in terms of physical and chemical properties.

Midwest Research Institute (MRI), together with the task officer and other cognizant EPA staff under Contract No. 68-02-1324, Task 25, developed the concept of a Fine Particle Emissions Information System (FPEIS). This system was designed to contain currently available fine particle source test measurements including source, collector and particulate parameters specific to the test. The system would be computerized for ease of manipulation, updating, and accessibility to the user community. The basic input to the system would be actual field test data from measurements of both controlled and uncontrolled sources.

The different phases of the FPEIS development were done under different tasks of Contract No. 68-02-1324. Under Task 25 of the contract, the basic characteristics of the FPEIS were developed and acquisition of the fine particle source test data begun. Task 36 of the contract continued the data acquisition phase initiated under Task 25. The acquired test reports were reviewed to establish data availability and identify the data gaps. Wherever there were some missing data, letter requests and telephone calls were made to the appropriate authors. An important activity of this task was the development of the input forms to code the data for entry into the data base.

MRI Systems Corporation of Austin, Texas, under separate contract to EPA, provided data processing support for the FPEIS using SYSTEM 2000, a data base management system available through EPA's National Computer Center at Research Triangle Park, North Carolina. SYSTEM 2000 provides several features which will enable FPEIS users to sort, compare, and retrieve information from FPEIS in almost any arrangement or manner that they choose. SYSTEM 2000 may be used with existing mathematical and statistical computer programs for a more comprehensive analysis of the FPEIS data.

Under Task 37, the elements of the data base were defined in a manner which conforms to the input requirements of SYSTEM 2000 for the construction of the data base.

The objectives of Task 42 have been:

1. To reduce the data collected under Tasks 25 and 36 to a form consistent with the FPEIS specifications defined previously in Task 37.

2. Submit the reduced data to the task officer for entry into the data base.

3. Prepare a final summary report on the development and present contents of the FPEIS.

The first and second objectives of this task were met by selecting an initial group of 27 reports collected under Tasks 25 and 36, and extracting from them the source/control device measurement information. This resulted in 52 test series representing 33 source types and a variety of conventional and novel control devices. These test series contain over 700 test runs utilizing primarily impactors of various types, but some optical particle counters, diffusion battery/condensation nuclei counters, and electrical analyzers were also utilized for the fine particle measurement. The data were keypunched, verified, and checked for coding and keypunching errors, copied onto a magnetic tape, and supplied to MRI Systems Corporation for entry into the data base system.

The following sections of this report describe the fine particle emissions information system, data acquisition efforts, general features of the available data, and reduction and assessment of particle size distribution data. The following sections also discuss the applicability and effectiveness of particulate control technology, an assessment of current level of fine particulate emissions, and an assessment of the current FPEIS data base.

Appendix A contains summary particle size distributions for the FPEIS data base. Appendix B is a summary of particulate sampling and sizing methods, and Appendix C includes a brief discussion of the adverse effects of fine particulates on human health. Appendices B and C have been included as complementary information for completeness.

This FPEIS Summary Report is intended, primarily, to summarize the system development activities and to evaluate the current FPEIS data base. Some terminology used here may be unclear to some readers. For a more detailed explanation of these terms and that of the data base itself, the reader is directed to the FPEIS Reference Manual and the FPEIS User Guide.

SECTION 2

DESCRIPTION OF THE FINE PARTICULATE EMISSION INFORMATION SYSTEM (FPEIS)

CONTENTS OF THE FPEIS

The FPEIS contains industrial source emission test data and novel, pilot or prototype control device evaluation data. It attempts to describe completely the aerosol from the point of its generation to the point at which it leaves the control device. General categories of information include source characteristics, control system descriptions, test characteristics, particulate mass train results, physical, biological, and chemical properties of the particulates, particulate size measurement equipment/method, and particulate size distribution data. Each category of information includes a number of related data elements, each of which is a unique variable essential for the description of the source tested.

Source Characteristics

This group of data elements describes the source that was tested, the name of the organization which performed the test, and reference from which the data were obtained. For source descriptions, the Source Classification Code (SCC) of the National Emission Data System (NEDS)[1] was used in order to provide cross references with other EPA data bases. The site name is distinguished from the source name so that a plant can be identified as well as the specific source or process operation. The Universal Transverse Mercator (UTM) coordinate system[2] is specified along with street, city, state, and zip code to pinpoint location of the site.

Three additional details include: (a) "Form Prepared by"; (b) "Tested by"; and (c) "Reference." Item (a) is important so that the individual responsible for encoding the data is identified in the event that follow-up is necessary for cross-checking of information, clarification, etc. Item (b) provides space for the name of the testing group performing the test. Item (c) identifies the report, journal article, etc., from which the information was acquired, if available.

Control Device Characteristics

This group includes data elements which describe the control system used (if any), and specify the design and operating parameters of the control system.

Standard nomenclature and units as given in the FPEIS Reference Manual are to be used to describe the control system and the design and operating parameters. The operating parameter values will be those measured during the time of the test.

Test Characteristics

This group of elements defines specific source operating parameters, including source operating mode, source operating rate, feed material type, and feed material composition. It also contains a description of the sampling location, stack gas conditions, Orsat analysis, and trace gas analysis. Additional test characteristics may be commented upon. These data elements attempt to describe fully the process and the aerosol at the sampling location, whether it is the inlet or outlet of the control device.

Particulate Mass Train Results

This group of data contains the results of mass sampling conducted during the test. Provisions are made for reporting front half and total mass concentrations and other comments on the mass train results.

Particulate Physical, Biological, and Chemical Characteristics

These groups of data elements contain the results of analyses performed on the collected particulate samples. Particulate physical properties include particle density and resistivity. Also required for these properties are information indicating the source of the data (measured or assumed). Any other physical properties, measured or assumed, are contained in comments.

Although at the present time few particulate samples are utilized for bioassay purposes, it is expected that in the future these kinds of tests will become more frequent. The bioassay data group provides data elements for specification of the test type as well as comments or results of these additional analyses.

The chemical composition group of data elements contain the chemical composition (in $\mu g/_{dn}m^3$) within a given size range and the particle boundary diameters. A maximum of nine size ranges are available in addition to the filter/total particulate range. The filter/total particulate chemical compositions are the results of the analyses performed on the particulate collected either by the mass sampling train or the total mass from all impactor stages. The chemical element or compound and its analysis method are given by the codes used in the SAROAD/SOTDAT data base system.[2]

Particulate Size Measurement Equipment/Method

This group of data elements identifies the specific measurement instrument/method used for collecting size distribution data and/or samples for chemical analysis. Items such as instrument name/method, the size range, collection surface, dilution ratio, measurement start time, sampling period and sampling rate, gas conditions at the instrument inlet along with appropriate comments are included. These data elements fully characterize the aerosol at the inlet of the measurement instrument or method.

Particle Size Distribution Data

This group of data elements provides the aerodynamic or Stokes diameter (see the discussion on page 33) range and mass or number concentration within this size range as measured by the instrument/method described above. To minimize computer storage and to allow users the freedom of calculating any size distribution, only raw data are contained in the system; however, particle size distributions, such as mass, surface, number and cumulative percent less than, and integral parameters of the size distribution are part of the output program options available to the user.

ORGANIZATION OF THE FPEIS

The organization of the FPEIS is shown in Figure 1. The input data to the FPEIS have generally been derived from either source test reports or published papers, although future tests may be reported on FPEIS Data Input Forms as standard practice. Each report or paper may have test data on one or more source/control device combinations. (An uncontrolled source is defined as a combination of source and no control devices.) All the data pertaining to a source/control device combination obtained at a certain time are given a test series number. For example, all data obtained on the Union Electric Meramec plant, Boiler Unit 1, as a part of "Refuse Firing Demonstration Study" were given five test series numbers. They are Test Series Nos. 19, 28, 29, 30, and 31, which were tests conducted during December 1973, November 1974, March 1975, May 1975, and November 1975, respectively. During each test, coal only and/or coal-plus-refuse was burned and the boiler was operated at various power loads. The present test series numbers have been assigned on an arbitrary basis; future additions will be given a master file number.

Each test series consists of a number of subsets which represent all the data pertaining to a given combination of source and control device operating parameters. The subseries ties different test runs together and gives a complete description of the aerosol for the various operating conditions of the source and control device.

The test run, which is a fundamental element of the FPEIS system, is defined as "any test measurement of a specific source/control device combination for a specific length of time, with specific particle size measuring equipment/method." For example, one size distribution measurement using the diffusion battery/condensation nuclei counter constitutes a run. Another size distribution measurement using an optical particle counter made at about the same time, with the source and control device operating parameters unchanged, constitutes another run. The mass train results such as those using EPA Method 5 are not treated as a test run but are included at the subseries level.

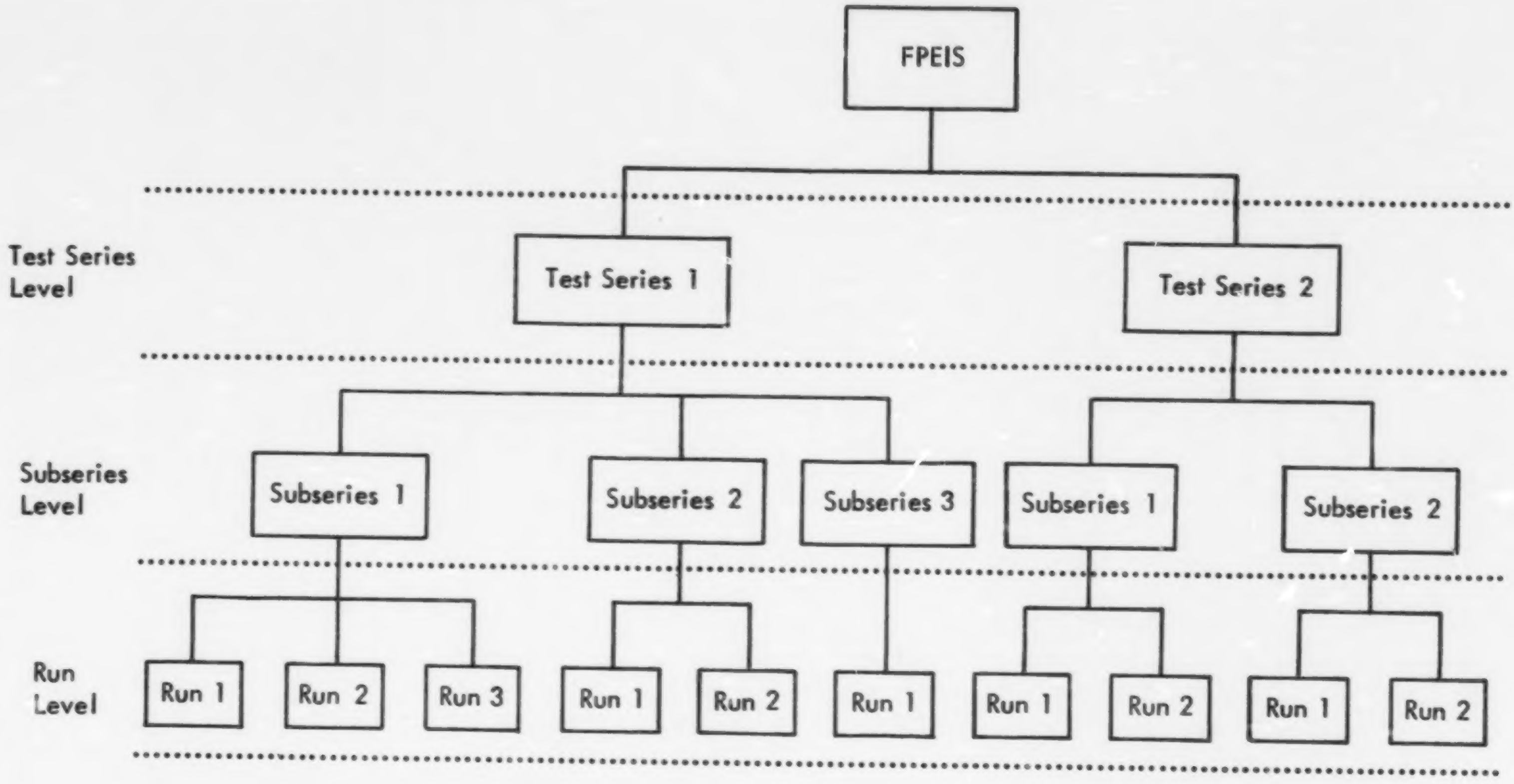
FPEIS
Test Series Level
Test Series 1
Test Series 2
Subseries Level
Subseries 1
Subseries 2
Subseries 3
Subseries 1
Subseries 2
Run Level
Run 1
Run 2
Run 3
Run 1
Run 2
Run 1
Run 1
Run 2
Run 1
Run 2

Figure 1. FPEIS Organization

The test run as defined above has both advantages and disadvantages. The disadvantages stem from the fact that the test run data being obtained by a single particle size measuring equipment/method may not cover the entire size spectrum of the aerosol. Therefore, it may be necessary to group several test runs representing data from different instruments to obtain a complete size distribution. On the other hand, this approach has flexibility, in that the data obtained by each instrument can be assessed. For example, if one makes six optical particle counter runs within the time of one impactor run, one can average all the optical particle counter runs and compare the average with the impactor run, or treat the six runs of the optical particle counter separately, getting a time resolution for the optical data.

An advantage of the test run, as defined, is that it simplifies data coding and verification. Furthermore, editing the data obtained by different instruments is also simplified. As an example, the cut points of an impactor which are found to be off by a factor of two can, at a later date, be changed very easily.

DATA INPUT FORMAT AND STRUCTURE

A tabulation of all the data elements of the FPEIS is shown in Table 1. Column 1 of this table shows the data input form number for various data elements. In Table 1, one can see that the source characteristics, test series remarks contained in the Data Input Form No. 1, and the control device characteristics excepting the device operating parameters contained in the Data Input Form No. 2 are at the test series level. The test characteristics, the control device operating parameters, and the particulate mass train results contained in the Data Input Forms Nos. 3 and 4, and the bioassay and chemical composition contained in Data Input Form No. 5 are at the subseries level. The measurement particulars and particle size distribution data contained in the Data Input Form No. 6 are at the test run level.

This arrangement of data elements minimizes the effort in coding the test data for FPEIS. For each test series, one needs to complete Data Input Forms Nos. 1 and 2 only once. For each test subseries Data Input Forms Nos. 3 through 5 need to be completed only once. Similarly, only one data input form (No. 6) is needed for one test run. The data coding effort is further reduced by not requiring one to complete the repeating information (see the user guide for examples and further explanation of labor-saving features). For example, suppose the inlet and outlet of a utility boiler equipped with an electrostatic precipitator are sampled 20 times with a single impactor operating at one set of flow rate and gas conditions. In coding this data, one needs to complete 101.* Computer programs are developed for data debugging and duplicating appropriate data elements.

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* Measurement instrument particulars and the boundary diameters for the initial run only. For subsequent runs, one has to code mass concentration data only.

TABLE 1. FPEIS DATA ELEMENTS AND THEIR LEVELS

Input data form No.	Test series level	Subseries level	Run level
1	A. Source Characteristics Source category (SCC I) Type of operation (SCC II) Feed material class (SCC III) Operating mode class (SCC IV) Site and source name Source address (street, city, state, zip code) UTM zone location and coordinates Test series start and finish date Tested by and reference B. Test Series Remarks		
2	C. Control Device(s) Characteristics Generic device type Device class and category Device commercial name Manufacturer Description Design parameter type and value		
3		D. Test Characteristics Test date, start, and finish time Source operating mode Source operating rate Percent design capacity Feed material and its composition Sampling location and its description Volume flow rate, velocity temperature and pressure Percent isokinetic sampling Orsat gas analysis and trace gas Composition Control Device(s) Operating Parameter and Value Remarks	
4		E. Particulate Mass Train Results Front half and total mass concentration Mass train comments F. Particulate Physical Properties Density Resistivity Others	
5		G. Bioassay Data Bioassay test type Test comments H. Chemical Composition Particle boundary diameters Sizing instrument calibrated or calculated SAROAD chemical and analysis method ID Concentration in filter/total Concentration in Ranges 1 through 9	
6			I. Measurement particulars Measurement instrument/method name Size range lower and upper boundary Collection surface Dilution factor Measurement start time and period Sample flow rate Sample temperature, pressure, and moisture content Comments J. Particulate Size Distribution Particle diameter basis (Aerodynamic or Stokes) Boundary diameter Concentration basis(mass or number) Concentration

DATA OUTPUT FORMATS

The potential for sorting and arranging the data contained in the FPEIS is virtually limitless; however, for the purposes of this project the format chosen for displaying all the information pertaining to a test series is shown in Tables 2 and 3 and Figure 2. These tables and the figure are identified at the top by the test series number, subseries number, inlet or outlet of the control device, and the test date and time.

Table 2 shows all the particulars of source, control device(s), test, particulate mass train, physical, biological, and chemical properties measurement equipment, and remarks.

Table 3 shows particle size distribution data including the mass ($\Delta M/\Delta \log D_{ae}$),* surface ($\Delta S/\Delta \log$ Dae), and number ($\Delta N/\Delta \log D_{ae}$) distributions. These three size distributions are based on the aerodynamic diameter. The first four columns of the table show boundary and geometric midpoint of both aerodynamic and Stokes particle diameters. At the bottom of the table the integral parameters of the three size distributions are shown; namely, total mass, total surface, and total number. Also, the percentages less than 1 μm, greater than 1 μm, less than 0.01 μm, 0.01 to 0.1 μm, 0.1 to 1.0 μm, 1 to 10 μm, and greater than 10 μm of mass, surface, and number are shown.

Figure 2 shows the three size distributions plotted as a function of the aerodynamic diameter. The ordinate range for the three distributions is normalized by dividing ordinate values by appropriate scales shown at the bottom of the plot. The scales are twice the total mass, surface, and number for the three distributions. The factor of 2 is just a scale factor, and does not affect the shape of the curves. The area under the curves within a given size range represents the mass, surface or number within that size range.**

POSSIBLE USES OF THE FPEIS

Figure 3 is a block diagram illustrating the potential role of the FPEIS as an important tool in fine particle program activities. This role encompasses both private and public sector efforts in: (a) identifying fine particulate emission sources; (b) determining the quantity and quality of such emissions; (c) evaluating various conventional and unconventional particulate control devices; and (d) evaluating and developing the sampling equipment and methodology used for fine particulate source measurement.

In Figure 3, three possible uses of the FPEIS are shown. These are the fine particle inventory, source/collector information exchange, and regulatory control method development.

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* For nomenclature and definitions, see page 34.

** Factor 2 is chosen because $\Delta \log D_{ae} \sim 0.3$ to 0.5. A detailed explanation of these plots are given in Appendix A.

TABLE 2. STATIONARY POINT SOURCE FINE PARTICULATE EMISSION INFORMATION SYSTEM

```
TEST SERIES NO:    2         SUB-SERIES NO:   1  INLET     DATE:  9/26/73    FROM  13:20  TO  16:15

       TESTED FROM  09/25/73  TO  09/27/73     BY: CONTROL SYSTEMS LABORATORY,EPA,RTP,NC
       REFERENCE:   STATNICK,RM, EPA-65012-74-111     OCT 74

I. SOURCE CHARACTERISTICS------------------------

       NEDS SCC CATEGORY:             INDUSTRIAL PROCES          SITE NAME      AMERICAN SMELTING + REFINING CO (ASARCO)
              OPERATION CLASS:        PRIMARY METALS             SOURCE NAME    COPPER SMELTER CONVERTER
              FEED MATERIAL CLASS:    COPPER SMELTER             ADDRESS
              OPERATION MODE CLASS:   CONVERTING                                TACOMA              ,WA
                                                                 UTM ZONE AND X-Y COORDS: 10      -0.0     -0.0

       SPECIFIC OPERATION: CONVERTING                            FEEDMATERIAL:
       OPERATING RATE:     500 T/DAY                             FFED MATERIAL COMPOSITION:

II. CONTROL DEVICE(S) CHARACTERISTICS------------

       UNIT 1

       DEVICE CATEGORY:    PARALLEL PLATE                         COMMERCIAL NAME:    ELECTRO STATIC PPTR
              CLASS:       CONVENTIONAL                           MANUFACTURER:       RESEARCH COTTREL,NL
       GENERIC TYPE:       ESP
       DESCRIPTION:
                                                                          OPERATING PARAMETERS
                 DESIGN PARAMETERS
                                                                   1)VOLUMETRIC GAS FLOW RATE       61.4 DNM3/S
                                                                   2)ELECTRODE AREA                 14813 M2
                                                                   3)CORONA CURRENT                 1243 MA
                                                                   4)SPARK RATE                     110 NO/MIN
                                                                   5)VOLUME PER UNIT ELECTRODE AREA 0.0042 M/S
                                                                   6)CORONA CURRENT DENSITY         0.084 MA/M2
                                                                   7)TEMPERATURE                    123 C

III. TEST CHARACTERISTICS ------------------------

       CONTROL DEVICE INLET         SAMPLING POINT DESCRIPTION: 3.5X7.3M DUCT IN UPSTREAM OF ESP DUCT     % ISOKINETIC: 104

       PROCESS CONDITIONS:   VOL FLOW=    61.4 DNM3/S  VELOCITY=   2.9 M/S  T=  123 C    P=   770 MMHG   WATER VAP %VOL=  5.8

       GAS COMPOSITION:      ORSAT-             CO2=   .40 %   CO=  0.69 %   O2= 20.20 %   N2= 79.40 %
                             TRACE GASSES(PPM)-SO2=30236, SO3=62.8

IV. PARTICULATE MASSTRAIN RESULTS --------------

       FRONT HALF= 3.350E+06 UG/DNM3   TOTAL= 3.690E+06   COMMENTS:
```

TABLE 2. (Concluded)

```
V. PARTICULATE PHYSICAL, BIALOGICAL AND CHEMICAL PROPERTIES

        DENSITY= 1.00 GM/CC ASSUMED  RESISTIVITY= 5.00E+11 OHM-CM ASSUMED

        CHEMICAL COMPOSITION DATA-----

              CHEMICAL AND ANALYSIS METHOD                  AMOUNT IN UG/DNM3 FOR PARTICLE DIAMETER(UM) RANGE OF
                                                 ------------------------------------------------------------------------------
                                                 FILTER/TOTAL   OVER  10     10 TO 1       1 TO 0.1   0.1 TO 0.01   UNDER 0.01

         1) ARSENIC                              616230.0000     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION
         2) CADMIUM                               40959.0000     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION
         3) CHROMIUM                                262.7300     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION
         4) COPPER                                  273.0600     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION
         5) MERCURY                                  67.5300     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION
         6) LEAD                                 321760.0000     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION
         7) ZINC                                 227673.0000     -0.0000     -0.0000     -0.0000     -0.0000     -0.0000
              ATOMIC ABSORPTION

VI. MEASUREMENT EQUIPMENT AND GAS CONDITIONS

        UNIT  1           1 RUNS

        EQUIPMENT NAME: BRINK-MODEL B               COLLECTION SURFACE/SUBSTRATE: UNCOATED SS CUPS
        SIZE RANGE:       .050  TO  10.000 MICRONS   SAMPLING RATE:    2.8 LPM     SAMPLING PERIOD:   15.0 MIN
        DILUTION FACTOR=   1.0        TEMP=  104 C   PRESSURE=        770 MMHG     WATER VAP %VOL =  5.8
        COMMENTS: IMPACTOR POSITION VERTICAL

VII. TEST SUB-SERIES REMARKS----------------------



VIII. TEST SERIES REMARKS-------------------------

        DUCT VELOCITY WAS OBTAINED AT ONLY ONE LOCATION AND RESULT CAN
        BE CONSIDERED APPROXIMATE
        SMOKE STACK HEIGHT 163 M
        10% OF THE SMELTER CONVERTER FLUE PASSES THRU AN ACID PLANT (SOX
        REMOVAL 96.7%) BEFORE REACHING THE ESP
        PARTICLE SIZE DISTRIBUTION DATA READ FROM GRAPH (AVE OF 3 RUNS)
        PARTICLE SIZE BOUNDARIES ARE ARBITRARILY CHOSEN
        SAMPLES DRIED 3HR AT 80C DESICCATED 2HR + WEIGHED ON METTLER H20T
        BALANCE
```

TABLE 3. PARTICLE SIZE DISTRIBUTION DATA

```
TEST SERIES NO:    2        SUB-SERIES NO:   1  INLET    DATE:  9/26/73    FROM  13:20  TO  16:15

IX. PARTICLE SIZE DISTRIBUTION DATA
    -------------------------------                                       PARTICLE DENSITY= 1.00 GM/CC  ASSUMED

  AERODYNAMIC DIA (UM)  PARTICLE DIA (UM)         DM           DM/DLDAE      DS          DS/DLDAE       DN        DN/DLDAE      CUM M
  --------------------  -----------------     (UG/DNM3)     (UG/DNM3)    (UM2/CC)     (UM2/CC)     (NO./CC)     (NO./CC)       (%)
     BNDRY     MID PT     BNDRY     MID PT

  UNIT  1  BRINK-MODEL B                                      RUNS   1

    10.000               10.000
     5.500      7.416     5.500      7.416     1.890E+06    7.279E+06    1.529E+06    5.889E+06    8.849E+03    3.408E+04
     2.500      3.708     2.500      3.708     1.100E+06    3.212E+06    1.780E+06    5.198E+06    4.120E+04    1.203E+05
     1.600      2.000     1.600      2.000     3.850E+05    1.986E+06    1.155E+06    5.959E+06    9.191E+04    4.742E+05
      .880      1.187      .880      1.187     3.110E+05    1.198E+06    1.573E+06    6.057E+06    3.555E+05    1.369E+06
      .400       .593      .400       .593     6.790E+04    1.983E+05    6.867E+05    2.005E+06    6.209E+05    1.813E+06
      .195       .279      .195       .279     6.560E+03    2.102E+04    1.409E+05    4.517E+05    5.751E+05    1.843E+06
      .050       .099      .050       .099     5.640E+02    9.542E+02    3.427E+04    5.798E+04    1.119E+06    1.893E+06

    INTEGRAL PARAMETERS----------------------------

                              TOTAL       LT 1.0      GT 1.0      LT 0.01     0.01-0.1     0.1-1.0     1.0-10.0     GT 10.0

       MASS     (UG/DNM3)   3.761E+06      2.0        98.0         0.0          .0          2.0        98.0          0.0
       SURFACE  (UM2/CC)    6.898E+06     12.5        87.5         0.0          .5         12.0        87.5          0.0
       NUMBER   (NO./CC)    2.812E+06     82.3        17.7         0.0        39.8         42.5        17.7          0.0
```

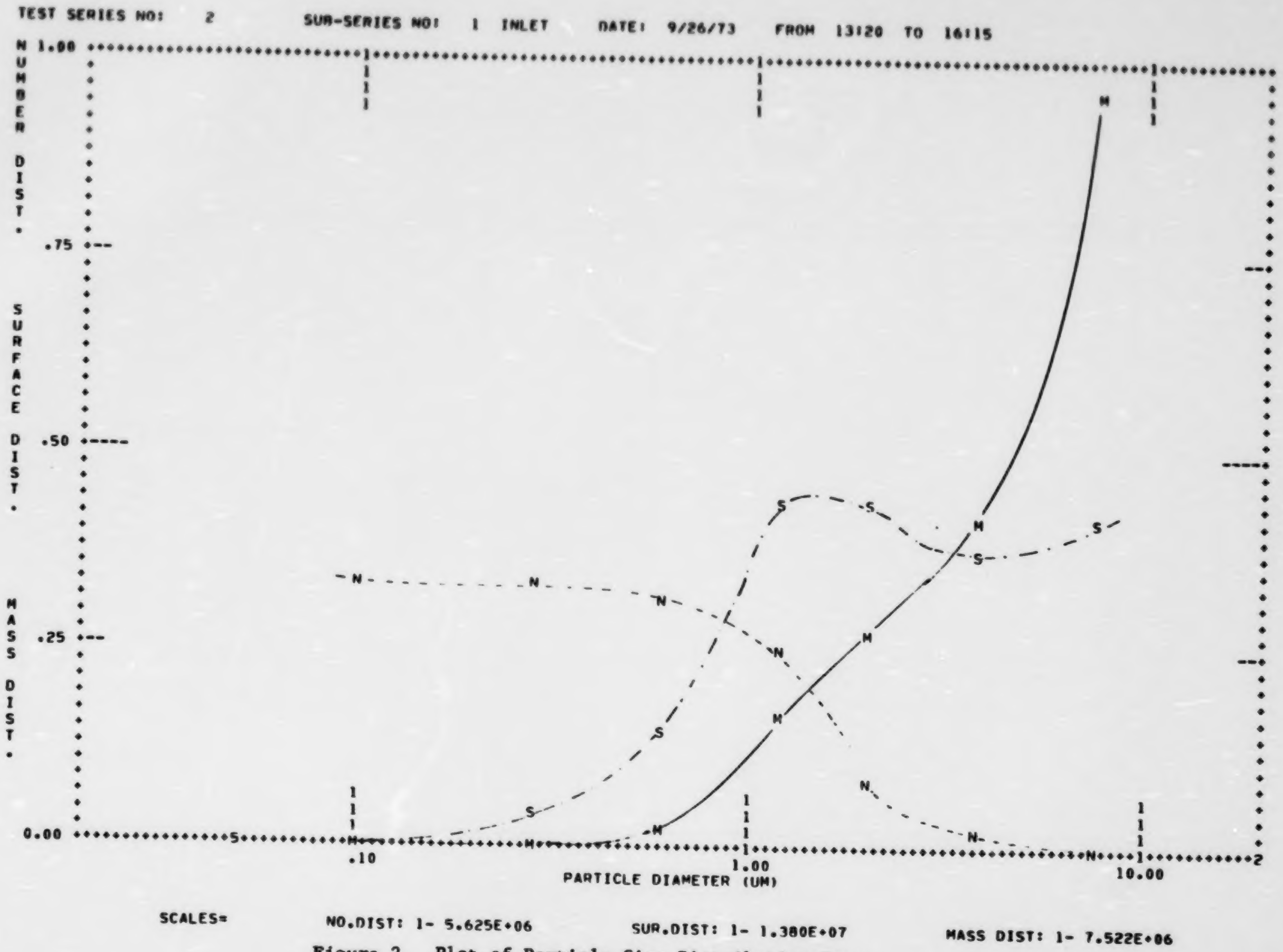

Figure 2. Plot of Particle Size Distribution Data

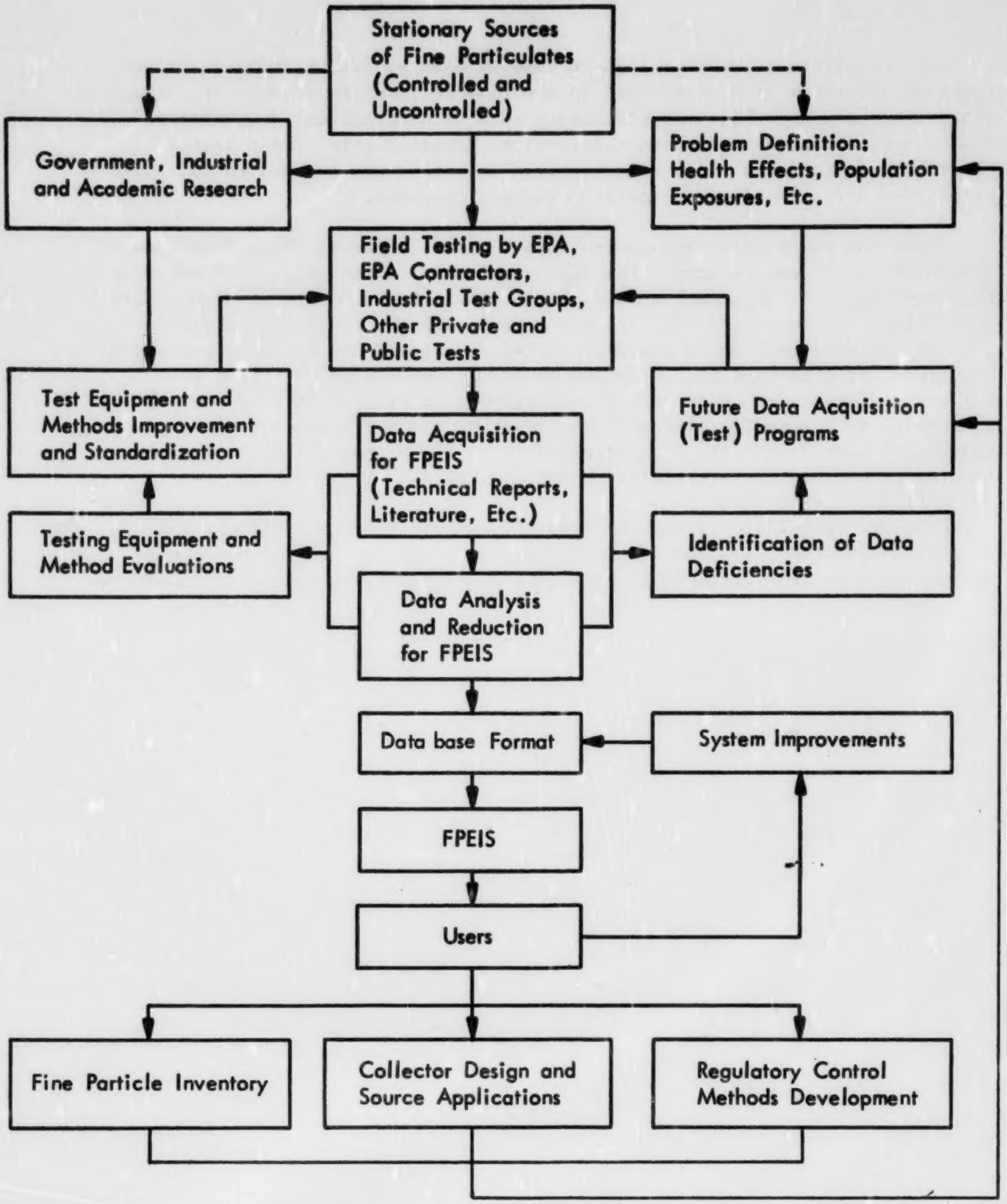
Stationary Sources of Fine Particulates (Controlled and Uncontrolled)
Government, Industrial and Academic Research
Problem Definition: Health Effects, Population Exposures, Etc.
Field Testing by EPA, EPA Contractors, Industrial Test Groups, Other Private and Public Tests
Test Equipment and Methods Improvement and Standardization
Future Data Acquisition (Test) Programs
Data Acquisition for FPEIS (Technical Reports, Literature, Etc.)
Testing Equipment and Method Evaluations
Identification of Data Deficiencies
Data Analysis and Reduction for FPEIS
Data base Format
System Improvements
FPEIS
Users
Fine Particle Inventory
Collector Design and Source Applications
Regulatory Control Methods Development

Figure 3. Role of FPEIS in Fine Particle Programs

A fine particle inventory can be used to display the relative contributions of several source categories to the fine particulate burden. In conjunction with other important considerations such as geographical distribution of source operations, hazard potential (health, chemical attack) and aesthetic contributions (opacity), the fine particle inventory can be used to establish priorities for allocation of control program resources.

From the source test measurements both at the inlet and outlet of a control device, one can determine the characteristics of the source and evaluate the performance of a control device. In addition, one can determine the characteristics of the particulate emissions from both the controlled and uncontrolled sources. Such information collected on various source/collector combinations could be used in the selection of a given control device for different sources, or in assessing the performance of a variety of devices as applied to a selected source operation. Directions for control methods (hardware) development or identification of promising new or novel control technology can also be ascertained using the FPEIS.

The availability of a current body of fine particle information, the fine particle inventory, and state-of-the-art device performance and application can also be of extensive usefulness in regulatory strategy development.

SECTION 3

DATA ACQUISITION

Acquisition of size distribution data relating to fine particulate emissions from various sources was an integral part of the program. Data acquisition was initiated under Task 25 and continued in Task 36. A variety of techniques were utilized including a systematic search of the technical literature, telephone and letter requests to EPA project officers, EPA and other government contractors, and industry sources.

Technical literature sources included:

Air Pollution Abstracts

Applied Science and Technology Index

Chemical Abstracts

Engineering Abstracts

A tabulation of individuals and agencies contacted is shown in Table 4.

The main objective of the continuing correspondence with these individuals and agencies was to request reports, reprints of journal articles, or acquire unpublished test data. Equally important was the continued communication with the individual, agency, or company so that test work in progress could be identified and follow-up requests made as appropriate. In addition, possible sources of test data which may have been overlooked could be uncovered.

Acquired test data sets were tabulated on a master file as received. A supplementary listing of "requested but not received," which included test work in progress, was also maintained. Appropriate follow-up action including letter requests and telephone calls were made in attempts to acquire reports and missing data.

Active data acquisition was terminated at the end of the fifth month of Task 36 in an effort to enable compilation of the acquired data in the FPEIS format. Test data received after this date were maintained in a separate listing.

TABLE 4. CONTACTS FOR FINE PARTICULATE SOURCE TEST DATA

EPA	Testing group	Industry	Other
James Abbott	APT, Inc.	Carborundum	State Air Pollution Agencies
Robert Ajax	Midwest Research Institute	Mikro Pul	Regional or County Agencies
A. B. Craig	Southern Research Institute	Research-Cottrell	University of Washington, Seattle, Washington (M. J. Pilat)
Dale Denny	GCA Technology	Industrial Gas Cleaning Institute	University of Maryland, College Park, Maryland (J. W. Gentry)
James Dorsey	York Research	Wheelabrator-Frye	Purdue University, West Lafayette, Indiana (R. B. Jacko)
Dennis Drehmel	PEDCo Environmental	Becker Industries Corporation	Ontario Ministry of the Environment
Gary Foley			
Dale Harmon			
Bruce Harris			
Bob Lorentz			
B. N. Murthy			
Leslie Sparks			
R. M. Statnick			
James Turner			
EPA Regional Offices (Director, Air Programs or Chief, Air Support)			
SOTDAT (James Southerland)			

A tabulation of the data for initial loading of the FPEIS is shown in Table 5. It is expected that more data will be accumulated by the time of first update due to the large number of tests conducted in recent months.

TABLE 5. TABULATION OF DATA FOR FPEIS DATA BASE--INITIAL LOADING

Test Series No.	Report's Author and Name[a/]	Testing Equipment	Source	Control Equipment	No. of Runs
1	Harris, D. B., and D. C. Drehmel, "Fractional Efficiency of Metal Fume Control as Determined by Brink Impactor," EPA/CSL (1973).	Brink Impactor Model B, 5-stage, Gelman type "A" final filter flow rate = 2.83 lpm Δp = 10"Hg	Zn Roaster	Wet ESP	4
2	Harris, D. B., and D. C. Drehmel, "Fractional Efficiency of Metal Fume Control as Determined by Brink Impactor," EPA/CSL (1973).	Brink Impactor Model B, 5-stage, Gelman type "A" final filter flow rate = 2.83 lpm Δp = 10"Hg	Cu Converter	Wet ESP	4
3	Harris, D. B., and D. C. Drehmel, "Fractional Efficiency of Metal Fume Control as Determined by Brink Impactor," EPA/CSL (1973).	Brink Impactor Model B, 5-stage, Gelman type "A" final filter flow rate = 2.83 lpm Δp = 10"Hg	Zn Sintering	Dry ESP	2
4	Harris, D. B., and D. C. Drehmel, "Fractional Efficiency of Metal Fume Control as Determined by Brink Impactor," EPA/CSL (1973).	Brink Impactor Model B, 5-stage, Gelman Type "A" final filter flow rate = 2.83 lpm Δp = 10"Hg	Pb Sintering	Baghouse (Orlon)	2
5	Harris, D. B., and D. C. Drehmel, "Fractional Efficiency of Metal Fume Control as Determined by Brink Impactor," EPA/CSL (1973).	Brink Impactor Model B, 5-stage, Gelman type "A" final filter flow rate = 2.83 lpm Δp = 10"Hg	Pb Blast Furnace	Baghouse (wool felt)	2
6	Statnick, R. M., "Measurement of SO_2, Particulate, and Trace Elements in a Copper Smelter Converter and Roaster/Reverberatory Gas Streams," EPA/CSL	Brink Impactor (Model B) at inlets, Andersen Sampler (Mark III) at outlets Brink flow rate = 2.83 lpm Andersen flow rate = 23.8 lpm	Cu Roaster and Reverberatory Furnace (ASARCO)	Dry ESP (pipe) and parallel type ESP	2

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a/ Complete references are provided beginning on page 47.

TABLE 5. (continued)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
7	Statnick, R. M., "Measurement of SO_2, Particulate, and Trace Elements in a Copper Smelter Converter and Roaster/Reverberatory Gas Streams," EPA/CSL	Brink Impactor (Model B) at inlets, Andersen Sampler (Mark III) at outlets Brink flow rate = 2.83 lpm Andersen flow rate = 23.8 lpm	Cu Converter	Plate type ESP	2
8	McCain, J. D., and W. B. Smith, "Lone Star Steel Steam-Hydro Air Cleaning System Evaluation," EPA-650/2-74-028 (1974).	Brink Impactor at inlet and Andersen Sampler at outlet. Optical particle counter and diffusion battery. Method 5 technique.	Open Hearth Furnace	Lone Star Steel Steam-Hydro Scrubber	38
9	Cooper, D. W., and D. P. Andersen, "Dynactor Scrubber Evaluation," GCA Corporation (1974)	Andersen (Mark III) 14 lpm	Test Aerosol from Dust Feeder	Dynactor Scrubber	50
10	Harris, D. B., "Tests Performed at Celotex Corporation, Goldsboro, North Carolina	Pilat Impactor	Asphalt Roofing	Afterburner	1
11	Harris, D. B., and J. A. Turner, "Particulate and SO_2/SO_3 Measurement Around an Anthracite Steam Generator Baghouse," EPA/CSL (1973)	Brink Impactor flow rate = 4.7 lpm Δp = 10"Hg	Pulverized Coal-Fired Boiler (anthracite) Pennsylvania Power and Light Company	Baghouse bulked weave, glass fiber bags with a Teflon finish	4
12	McKenna, J. D., "Applying Fabric Filtration to Coal-Fired Industrial Boilers: A Preliminary Pilot Scale Investigation," Enviro-Systems and Research, Inc. (1974)	Andersen Sampler	Coal-Fired Industrial Boiler Kerr Industries, Concord, North Carolina	Nomex Baghouse	3
13	Cowherd, C., et al., "Hazardous Emission Characterization of Utility Boilers," EPA-650/2-75-066	Brink Impactor	Utility Boiler	Cyclone	6

TABLE 5. (continued)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
15	Statnick, R. M., and D. C. Drehmel, "Fine Particulate Control Using SO_2 Scrubbers," EPA (1974).	Brink Impactor and Andersen Sampler. Total Particulates using EPA Method 5.	Coal-Fired Power Boiler (TVA, Shawnee)	TCA Scrubber	14
16	Statnick, R. M., and D. C. Drehmel, "Fine Particulate Control Using SO_2 Scrubbers," EPA (1974).	Brink Impactor and Andersen Sampler. Total Particulates using EPA Method 5.	Coal-Fired Power Boiler (TVA, Shawnee)	Venturi Scrubber	4
17	Statnick, R. M., and D. C. Drehmel, "Fine Particulate Control Using SO_2 Scrubbers," EPA (1974).	Brink Impactor and Andersen Sampler. Total Particulates using EPA Method 5.	No. 6 Fuel Oil Fired Power Boiler (Mystic)	Venturi MgO Scrubber	8
18	Riggenbach, J. D., E. D. Johnson and M. K. Hamlin, "Measurement of Particulate Grain Loadings, Particle Size Distribution, and Sulfur Gas Concentrations at Hoerner Waldorf's Pulp and Papermill No. 3 Recovery System, Vols. I, II, and III, Environmental Science and Engineering, Inc.	Brink Impactor	Pulp and Papermill Recovery Biler	ESP	38
19	Shannon, L. J., et al., "St. Louis/Union Electric Refuse Firing Demonstration Air Pollution Test Report."	Total Mass by EPA Method 5 Brink Impactor and Andersen Sampler	Coal-Fired Utility Boiler Refuse Firing Demonstration, St. Louis/Union Electric	ESP	26
20	McCain, J. D., "Evaluation of Aronetics Two-Phase Jet Scrubber," EPA-650/2-74-129	Brink Impactor, Andersen Sampler Method 5, Optical Particle Counter, Diffusion Battery + CNC	Ferro-Alloy Electric Arc Furnace	Aronetics Two-Phase Jet Scrubber	41
21	Bosch, J. C., M. J. Pilat, and B. F. Hrutfiord, "Size Distribution of Aerosols From a Kraft Mill Recovery Furnace," Tappi 54(11):1871 (1971).	Pilat Impactor	Kraft Mill Recovery Furnace	ESP	4

Test Series Nos. 14 and 47 has missing or invalid data and will be coded when test data are available.

TABLE 5. (continued)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
22	McGarry, F. J., and C. J. Gregory, "A Comparison of the Size Distribution of Particulates Emitted From Air, Mechanical, and Steam Atomized Oil-Fired Burners," JAPCA, 22(8):636 (1972).	Andersen Sampler	Air Atomized Oil-Fired Boiler	ESP	1
23	McGarry, F. J., and C. J. Gregory, "A Comparison of the Size Distribution of Particulates Emitted From Air, Mechanical, and Steam Atomized Oil-Fired Burners," JAPCA, 22(8):636 (1972).	Andersen Sampler	Mechanical Atomized Oil-Fired Boiler	ESP	1
24	McGarry, F. J., and C. J. Gregory, "A Comparison of the Size Distribution of Particulates Emitted From Air, Mechanical, and Steam Atomized Oil-Fired Burners," JAPCA, 22(8):636 (1972).	Andersen Sampler	Steam Atomized Oil-Fired Boiler	ESP	1
25	Lee, R. E., Jr., H. L. Crist, A. E. Riley, and K. E. MacLeod, "Concentration and Size of Trace Metal Emissions From a Power Plant, a Steel Plant, and a Cotton Gin," Env. Sci. and Tech., 9(7):643 (1975).	UW Mark III Sampler	Emissions from a Power Plant	ESP	2
26	Lee, R. E., Jr., H. L. Crist, A. E. Riley, and K. E. MacLeod, "Concentration and Size of Trace Metal Emissions From a Power Plant, a Steel Plant, and a Cotton Gin," Env. Sci. and Tech., 9(7):643 (1975).	UW Mark III Sampler	Emissions from a Steel Plant	Baghouse	2

TABLE 5. (continued)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
27	Lee, R. E., Jr., H. L. Crist, A. E. Riley, and K. E. MacLeod, "Concentration and Size of Trace Metal Emissions from a Power Plant, a Steel Plant, and a Cotton Gin," Env. Sci. and Tech., 9(7)643 (1975).	UW Mark III Sampler	Emissions from a Cotton Gin	Wet Scrubber	2
28	"St. Louis-Union Electric Refuse Fuel Project," MRI Project No. 3821-C(4), January 1975	Brink and Andersen Impactors	Coal-Fired Utility Boiler Refuse Firing Demonstration	ESP	67
29	"St. Louis-Union Electric Refuse Fuel Project," MRI Project No. 4033-C, Monthly Report No. 1	Brink and Andersen Impactors	Coal-Fired Utility Boiler Refuse Firing Demonstration	ESP	12
30	"Test and Evaluation Program for St. Louis-Union Electric Refuse Fuel Project," MRI Project No. 4033-C, Monthly Report No. 4	Brink and Andersen Impactors	Coal-Fired Utility Boiler Refuse Firing Demonstration	ESP	43
31	"Test and Evaluation Program for St. Louis-Union Electric Refuse Fuel Project," MRI Project No. 4033-C, Monthly Report No. 11	Brink and Andersen Impactors	Coal-Fired Utility Boiler Refuse Firing Demonstration	ESP	19
32	Toca, F. M., "Lead and Cadmium Distribution in the Particulate Effluent from a Coal-Fired Boiler," Ph.D. Thesis, University of Iowa, Ames, Iowa, July 1972	Andersen Ambient Sampler	Coal-Fired Boiler	ESP	5
33	Baladi, E., "Particle Size Distribution Tests for Beker Industries Corporation," MRI Project No. 5-1379-C	Brinks Impactor	Phosphate Rock Calciner	Venturi Scrubber	5

TABLE 5. (continued)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
34	Gooch, J. P., and J. D. McCain, "Particulate Collection Efficiency Measurements on a Wet Electrostatic Precipitator," EPA-650/2-75-033	Brink Andersen Samplers Optical Particle Counter, Diffusion Battery and CN Counter	Aluminum Reduction Cells	ESP Preceded by Spray Towers	17
35	Bradway, R. M., and R. W. Cass, "Fractional Efficiency of a Utility Boiler Baghouse," EPA-600/2-75-013-a	Andersen Impactor	Coal-Fired Boiler	Baghouse	86
36	McKenna, J. D., J. C. Mylock, and W. O. Lipscomb, "Applying Fabric Filtration to Coal-Fired Industrial Boilers," EPA-650/2-74-058-a	Andersen Impactor	Coal-Fired Boiler	Nomex Baghouse	28
37	McKenna, J. D., J. C. Mylock, and W. O. Lipscomb, "Applying Fabric Filtration to Coal-Fired Industrial Boilers," EPA-640/2-74-058-a	Andersen Impactor	Coal-Fired Boiler	Teflon Felt (Style 1) Baghouse	7
38	McKenna, J. D., J. C. Mylock, and W. O. Lipscomb, "Applying Fabric Filtration to Coal-Fired Industrial Boilers," EPA-650/2-74-058-a	Andersen Impactor	Coal-Fired Boiler	Teflon Felt (Style 2) Baghouse	5
39	McKenna, J. D., J. C. Mylock, and W. O. Lipscomb, "Applying Fabric Filtration to Coal-Fired Industrial Boilers," EPA-650/2-74-058-a	Andersen Impactor	Coal-Fired Boiler	Gore-Tex/Nomex Baghouse	11
40	McKenna, J. D., J. C. Mylock, and W. O. Lipscomb, "Applying Fabric Filtration to Coal-Fired Industrial Boilers," EPA-650/2-74-058-a	Andersen Impactor	Coal-Fired Boiler	Dralon Baghouse	7

TABLE 5. (continued)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
41	McCain, J. D., "Evaluation of Centrifield Scrubber," EPA-650/2-74-129-a	Brinks Andersen Impactors Diffusional, Optical and Electrical Methods	Asphalt Dryer Burning No. 2 Fuel Oil	1. Coarse Cyclone 2. Secondary Collector 3. Scrubber	31
42	Cooper, D. W., "Pentapure Impinger Evaluation," EPA-650/2-75-024-a	Andersen In-Stack Impactor	Gray Iron Foundry	Pentapure Impinger	12
43	Yost, K. J. et al., "The Environmental Flow of Cadmium and Other Trace Metals," Progress Report NSF (RANN) Grant GI-35106, Purdue University, West Lafayette, Indiana	Andersen Impactor	Zinc Coker Plant	-	1
44	Yost, K. J. et al., "The Environmental Flow of Cadmium and Other Trace Metals," Progress Report NSF (RANN) Grant GI-35106, Purdue University, West Lafayette, Indiana	Andersen Impactor	Zinc Vertical Retort	Baghouse	3
45	Yost, K. J. et al., "The Environmental Flow of Cadmium and Other Trace Metals," Progress Report NSF (RANN) Grant GI-35106, Purdue University, West Lafayette, Indiana	Andersen Impactor	Steel Mill Open Hearth Furnace	ESP	6
46	Yost, K. J. et al., "The Environmental Flow of Cadmium and Other Trace Metals," Progress Report NSF (RANN) Grant GI-35106, Purdue University, West Lafayette, Indiana	Andersen Impactor	Municipal Incinerator	Scrubber	1
48	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark II and Andersen Impactors	Urea Prilling Tower	Valve Tray	12

TABLE 3. (concluded)

Test Series No.	Report's Author and Name	Testing Equipment	Source	Control Equipment	No. of Runs
49	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark III and Andersen Impactors	Potash Dryer	Scrubber	17
50	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark III and Andersen Impactors	Coal-Fired Boiler	TCA Scrubber	6
51	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark III and Andersen Impactors	Coal-Fired Boiler	Venturi Scrubber	6
52	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark III and Andersen Impactors	Salt Dryer	Wetted Fiber Scrubber	16
53	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark III and Andersen Impactors	Salt Dryer	Impingement Plate Scrubber	12
54	Calvert, S., N. J. Jhaveri, and S. Yung, "Fine Particle Scrubber Performance Tests," EPA-650/2-74-093	UW Mark III and Andersen Impactors	Iron Melting Cupola	Venturi Rod Scrubber	18

SECTION 4

GENERAL FEATURES OF AVAILABLE DATA

The purpose of this section is to discuss the general features of the data including the nature of the raw data and the forms in which they exist, the instruments used in collecting the particle size distribution data and their problems.

Table 5 shows the fine particle test data contained in the FPEIS at the present time and the source, control device(s), and testing equipment for each test series. Table 6 (discussed later in Section 6) summarizes the FPEIS data based on source type and control device type. These two tables illustrate that the bulk of the data has been collected on utility and industrial boilers equipped with electrostatic precipitators, and most of the particle size distribution data were obtained with inertial impactors.

Most source tests of the present data base were conducted for purposes other than obtaining fine particulate size distribution data. Furthermore, most reports were not written solely for the purpose of reporting test data. The data retrieval was further complicated by lack of standard procedures for collecting data. Considerable time had to be spent on each test report to gather the information required by the FPEIS. Even the most important information such as source location, control device description, particle density, and measurement instrument details was either inadequately described or not mentioned in the report.

The available data were found in English units, metric units, and mixed units. For example, Method 5 mass train results were reported in units of grains per standard cubic foot (gr/scf), grams per standard cubic meter (g/scm), and grains per standard cubic meter (gr/scm). Also, the data were reported in units of grains per cubic foot (gr/f^3), milligrams per cubic meter (mg/m^3), micrograms per cubic meter ($\mu g/m^3$), etc., necessitating temperature and pressure corrections. (Refer to Table 8, page 46 for conversion factors.)

There were different means of presenting the particle size distribution data. Some of the reports displayed data only in graphical form. The graphs were either cumulative mass distributions or differential mass distributions; the particle diameters were either aerodynamic diameter or Stokes diameter. Other reports displayed data in graphical form supplemented by a tabulation of reduced data. In a few cases raw data were included as an appendix.

TABLE 6. FPEIS DATA CLASSIFICATION BASED ON SOURCE AND CONTROL DEVICE TYPE

		ESP		Conventional scrubber		Novel scrubber		Baghouse		Other			
Source type	Operation	TS No.	No. of runs	TS No.	No. of runs	TS No.	No. of runs	TS No.	No. of runs	Device name	TS No.	No. of runs	Subtotal
1. Stationary combustion sources	Coal-fired utility boiler	19,25,28,29, 30,31,32	174	16,50,51	16	15	14	11,35	90	Cyclone	13	6	300
	Oil-fired utility boiler	22,23,24	3	17	8	--	--	--	--		--	--	11
	Coal-fired industrial boiler	--	--	--	--	--	--	12,36,37, 38,39,40	61		--	--	61
2. Iron and steel plants	Open hearth furnace	45	6	--	--	8	38	26	2		--	--	46
	Electric arc furnace	--	--	--	--	20	41	--	--		--	--	41
	Gray iron foundary	--	--	54	18	42	12	--	--		--	--	30
3. Nonferrous plants	Cu conveyor	2,7	6	--	--	--	--	--	--		--	--	6
	Cu roasting/reverberatory	6	2	--	--	--	--	--	--		--	--	2
	Zn roaster	1	4	--	--	--	--	--	--		--	--	4
	Zn sintering	3	2	--	--	--	--	--	--		--	--	2
	Pb sintering	--	--	--	--	--	--	4	2		--	--	2
	Pb blast furnace	--	--	--	--	--	--	5	2		--	--	2
	Al reduction cells	34	17	--	--	--	--	--	--		--	--	17
	Zn coker plant	--	--	--	--	--	--	--	--	Unknown	43	1	1
	Zn vertical retort	--	--	--	--	--	--	44	3		--	--	3
4. Asphalt plants	Asphalt aggregate drying	--	--	41	31	--	--	--	--		--	--	32
5. Pulp and paper	Kraft mill recovery furnace	18,21	42	--	--	--	--	--	--	Afterburner	10	1	42
6. Chemical industry	Phosphate rock calciner	--	--	33	5	--	--	--	--		--	--	5
	Pot ash dryer	--	--	49	17	--	--	--	--		--	--	17
	Salt dryer	--	--	52,53	28	--	--	--	--		--	--	28
	Urea prilling	--	--	48	12	--	--	--	--		--	--	12
7. Other	Municipal incinerator	--	--	46	1	--	--	--	--		--	--	1
	Dust feeder	--	--	--	--	9	50	--	--		--	--	50
	Cotton gin	--	--	27	2	--	--	--	--		--	--	2
		Subtotal	256		138		155		160			8	717

Use of the standard FPEIS Data Input Forms by testing groups in the future will greatly simplify the process of preparing data for input to the data base. In this way, the standard FPEIS units protocol will be followed and, more importantly, complete data sets may be obtained. The greatest difficulty associated with the initial loading of FPEIS data has been the incompleteness of the data sets received.

SECTION 5

REDUCTION AND ASSESSMENT OF PARTICLE SIZE DISTRIBUTION DATA

Reduction and preliminary asssessment of particle size distribution data were necessary prior to entering them in the FPEIS. The following subsections present the data reduction procedures and discuss the quality of data.

REDUCTION OF PARTICLE SIZE DISTRIBUTION DATA

Aerosols can be characterized in a number of different ways. The choice depends upon the particular need for characterization. For example, in the field of air pollution one is mainly interested in the concentration and size distribution based on aerosol mass. The FPEIS output provides concentration and size distributions based on particle mass, surface, or number. Moreover, these distributions are provided on both a differential and a cumulative basis.

Although there are a variety of data reduction techniques in the literature, a simple, general and straightforward procedure has been adopted. Each run consists of several classes or stages. The raw data generally are mass or number concentrations in each class and the upper and lower aerodynamic or Stokes boundary diameters. For example, in the case of impactors, the mass collected on each stage per unit volume of gas sampled and the effective cut-off diameter of each stage are available. The upper boundary for the first stage and lower boundary for the final filter can usually be estimated.

The following equations are used in the data reduction.

$$\text{Diameter midpoints} = (\text{upper boundary} \times \text{lower boundary})^{1/2} \qquad (1)$$

$$\text{Aerodynamic diameter, } D_{ae} = D_p \left[\frac{\rho_p \, C_{D_p}}{C_{D_{ae}}} \right]^{1/2} \qquad (2)$$

where D_p = particle diameter (Stokes or sedimentation diameter)

ρ_p = particle density

C_D = Cunningham slip correction factor

$$= 1 + \frac{2\lambda}{D_p} [1.246 + 0.42 \exp(-0.87\, D_p/2\lambda]$$

λ = mean free path of gas molecules

$C_{D_p} = 1 + 0.162/D_p$ for air at NTP (D_p is in μm, reference temperature and pressure are 20°C, 760 mm Hg)

Since D_{ae} appears on both sides of Eq. (2), an interative technique is needed to solve this equation.

D_{pi} = particle diameter midpoint (μm)

ΔM_i = mass in $\mu g/m^3$ within the class

$$= \frac{\pi}{6} D_{pi}^{\;3}\ \rho_p\ \Delta N_i \qquad (3)$$

ΔN_i = number of particles per cubic centimeter within the class (no./cm^3)

ΔS_i = surface area of particles within the class ($\mu m^2/cm^3$)

$$= \pi D_{pi}^{\;2}\ \Delta N_i \qquad (4)$$

The underlying assumption here is that all the particles are spherical which in many cases is not valid. For nonspherical particles, a shape factor will enter Eq. (2) whose value depends upon the definition of the diameter of the nonspherical particle itself.

The differential size distributions are calculated in the following way:

$$\Delta \log D_{ae_i} = \log_{10} \left[\frac{D_{ae} \text{ upper boundary of class i}}{D_{ae} \text{ lower boundary of class i}} \right] \qquad (5)$$

$$(\Delta X/\Delta \log D_{ae})_i = \frac{\Delta X_i}{\Delta \log D_{ae_i}} \qquad (6)$$

where x is mass, surface or number concentration.

The distributions $\Delta M/\Delta \log D_{ae}$, $\Delta S/\Delta \log D_{ae}$ or $\Delta N/\Delta \log D_{ae}$ are usually displayed on a semi-log graph with the distribution function as the ordinate and log D_{ae} as the abscissa.

The cumulative size distributions are calculated by summing mass, surface or number concentrations in the classes below the class of interest, and dividing it by the total concentration.

$$\text{cum \% less } x_i = \left(\sum_{k=i+1}^{j} \Delta X_k \Big/ \sum_{k=1}^{j} \Delta X_k \right) 100 \qquad (7)$$

where X = mass, surface or number

x = particle diameter

j = number of classes + 1

i = class number of interest.

Note that particle sizes decrease with increasing class number.

ASSESSMENT OF THE QUALITY OF PARTICLE SIZE DISTRIBUTION DATA

Quality assessment of data begins with source testing, and all factors affecting results should be reported. A report of the problems encountered and solutions sought at the time of the test will be invaluable to data evaluation, and to future source testing.

The problems discussed in various test reports can be grouped into three classes of problems, namely, sampling problems, measurement problems, and data reporting problems. The data reporting problems are mainly due to a lack of standard procedures for collecting and reporting data. These problems are expected to be minimized because of the availability of Data Input Forms developed for the FPEIS. The sampling and measurement problems are discussed below.

Sampling Problems

Obtaining a representative sample requires careful selection of the sampling site and proper sampling by the instrument. Nonideal sampling locations, improperly designed or inadequate ports for *in situ* sampling, and stacks containing effluent from one or more sources with varying operating cycles are often encountered. Flow disturbances such as those caused by a bend or flow fluctuations caused by process variations result in nonuniformity of particulate concentration profile.

Isokinetic sampling requires that the sample be removed from the mainstream at the same velocity and flow direction as that of the mainstream. Isokinetic sampling has not always been possible, especially when the sampling duration is short and flow fluctuations are large.

Samplers such as impactors have to be operated at constant flow rates. If there are significant variations in flow velocity across the duct, traversing with the sampler is desired. However, traversing with impactor samplers is not done.

Design of the sampling train, especially for *ex situ* sampling is another area of concern. The sampling lines must be properly insulated to minimize sampling line wall loss and growth of particles by condensation. The sampling lines should be designed to minimize coagulation and wall losses, which was not done in some tests.

Measurement Instrument Problems

Most of the particle size distribution data in the FPEIS have been obtained using inertial impactors. A few runs have also been made with an optical particle counter, diffusion battery along with condensation nuclei counter, and Whitby electrical aerosol analyzer.

Impactors should be calibrated if reliable data are required. None of the impactors used in collecting FPEIS data at this time have been adequately calibrated. The stage cut points are almost always theoretically calculated rather than experimentally determined. Other problems identified with impactors are:

1. Particle bounce due to high jet velocity.

2. Scouring of the adhesive coating on impactor plates under high jet velocity conditions.

3. De-agglomeration of aggregates within the impactor resulting in distorted aerosol size distributions.

4. Heavy loading on the collection plates due to high aerosol concentration in the sampled duct. This problem is a common situation when source outlets or collector inlets are sampled. When collection plates are overloaded, particle reentrainment occurs and particles are carried over into subsequent stages, distorting the size distribution.

5. Formation of tall conical heaps of particulate directly below the jets.

6. Gas condensation within the impactor which overloads the initial stages of the impactor, wets the substrate, or in certain cases, results in a chemical reaction between the condensed gases and the collection substrate.

7. Loss of substrate weight.

8. Sampling with a low flow rate impactor at the collector inlet for very short sampling times (seconds) to minimize overloading due to high aerosol concentration. Sampling with a high flow rate impactor at the collector outlet for very long periods of time (hours) because of low aerosol concentration. This procedure is good provided the samples are taken concurrently, and that several inlet samples are taken during the time the outlet sample is obtained.

One would expect a good correlation between mass train (EPA Method 5) results and total mass measured by impactors under similar test conditions. However, this is not the case for several tests due to an isokinetic sampling and nontraversing of the impactor.

Only ex situ sampling is possible with the presently available automatic instruments. There is frequently a severe loss of particulates in the sample conditioner and sampling lines. This loss reduces the absolute concentrations measured by these instruments.

Typically, source test reports contain data of all runs, successful as well as unsuccessful; therefore, the FPEIS data were screened before coding. The obvious bad runs were eliminated, and the rest of the data were entered into the system with appropriate comments. These comments should be helpful to the FPEIS user in the data evaluation. It should be noted again that no test series completely satisfied the data requirements on input protocol of the FPEIS.

SECTION 6

APPLICABILITY AND EFFECTIVENESS OF PARTICULATE CONTROL TECHNOLOGY

The available data classified according to source type and control device type are shown in Table 6. Data gaps clearly exist. However, the available data cover some important sources/collector combinations, and could be used for their preliminary evaluation.

At present FPEIS has a sizable amount of data on electrostatic precipitators (ESP), conventional and novel wet scrubbers, and baghouses. The data show that these four types of control devices are applied to coal-fired utility boiler emissions, a major source of particulates. In addition, electrostatic precipitators were applied to ferrous and nonferrous furnaces, and to Kraft mill recovery furnaces. Wet scrubbers were employed in the iron and steel industry and in the chemical industry.

The FPEIS contains, for the most part, particle size distribution data at the inlet and outlet of control devices from which the fractional efficiency of the device could be obtained. Deriving the fractional efficiency curves from the present data is complicated by the fact that the inlet and outlet data are not obtained with the same particle size measuring device or under similar conditions. The inlet boundary diameters are different from those of the outlet. So, for fractional efficiency calculations, a computer program which curves to fit the inlet and outlet particle size distribution data, and which calculates the mass fraction within a given size range, is needed. Because of the lack of such a program, the average of total mass concentrations at the inlet and outlet were computed from which the overall collection efficiency was determined.

Table 7 shows the total inlet and outlet mass concentration averages and overall collection efficiency for various source/collector combinations contained in the FPEIS. The mass concentrations are given in units of micrograms per normal cubic meter. In this table, one can see that the average overall efficiencies of electrostatic precipitators, conventional scrubbers, novel scrubbers, baghouses and cyclones, applied to a coal-fired utility boiler are 92.9, 92.3, 95.8, 99.7, and 47.3%, respectively. Electrostatic precipitators appear to be not very efficient when applied to nonferrous plants. Baghouses generally have overall efficiencies over 99% for the source types contained in the data base. Wet scrubbers are applied mostly in the chemical industry

TABLE 7. AVERAGE TOTAL INLET AND OUTLET MASS CONCENTRATION ($\mu g/m^3$) AND OVERALL COLLECTION EFFICIENCY ACCORDING TO SOURCE TYPE AND CONTROL DEVICE TYPE

Source type	Operation	ESP			Conventional scrubber			Novel scrubber			Baghouse			Other			
		Inlet	Outlet	η	Inlet	Outlet	η	Inlet	Outlet	η	Inlet	Outlet	η	Device name	Inlet	Outlet	η
1. Stationary combustion sources	Coal-fired utility boiler	3.016E6	1.421E4	92.9	1.593E6	6.819E4	92.3	7.448E5	3.138E4	95.8	9.573E6	1.444E4	99.7	Cyclone	4.101E6	2.162E6	47.3
	Oil-fired utility boiler	2.011E6	-	-		*		-	-	-	-	-	-		-	-	-
	Coal-fired industrial boiler	-	-	-	-	-	-	-	-	-	4.574E5	1.613E4	98.5		-	-	-
2. Iron and steel plants	Open hearth furnace	1.333E6	1.147E4	99.1	-	-	-	2.824E6	2.922E3	99.9	1.324E5	1.40E2	99.9		-	-	-
	Electric arc furnace	-	-	-	-	-	-	1.164E6	2.767E4	97.6	-	-	-		-	-	-
	Gray iron foundry	-	-	-	2.660E6	2.876E4	98.9		*		-	-	-		-	-	-
3. Nonferrous plants	Cu converter	2.028E6	2.563E5	85.9	-	-	-	-	-	-	-	-	-		-	-	-
	Cu roasting/reverberatory furnace		*		-	-	-	-	-	-	-	-	-		-	-	-
	Zn roaster	2.619E5	1.266E5	51.7	-	-	-	-	-	-	-	-	-		-	-	-
	Zn sintering	3.394E6	1.409E6	58.5	-	-	-	-	-	-	-	-	-		-	-	-
	Pb sintering	-	-	-	-	-	-	-	-	-	5.259E5	1.806E3	99.7		-	-	-
	Pb blast furnace	-	-	-	-	-	-	-	-	-	1.658E4	7.295E3	56.0		-	-	-
	Al reduction cells	8.226E4	8.53E2	99.0	-	-	-	-	-	-	-	-	-		-	-	-
	Zn coker plant	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
	Zn vertical retort	-	-	-	-	-	-	-	-	-	-	2.856E5	-	Unknown	-	4.130E5	-
4. Asphalt plants	Asphalt aggregate drying	-	-	-	5.183E7	8.037E4	99.8	-	-	-	-	-	-	Afterburner	-	*	-
5. Pulp and paper industry	Kraft mill recovery furnace	8.225E6	1.319E5	84.0	-	-	-	-	-	-	-	-	-		-	-	-
6. Chemical industry	Phosphate rock calciner	-	-	-	2.220E4	-	-	-	-	-	-	-	-		-	-	-
	Pot ash dryer	-	-	-	8.024E5	2.185E5	72.8	-	-	-	-	-	-		-	-	-
	Salt dryer	-	-	-	1.173E5	9.966E3	91.7	-	-	-	-	-	-		-	-	-
	Urea prilling	-	-	-	2.572E4	1.703E4	33.8	-	-	-	-	-	-		-	-	-
7. Other	Municipal incinerator	-	-	-	-	1.163E5	-	-	-	-	-	-	-		-	-	-
	Dust feeder	-	-	-	-	-	-	7.141E5	5.241E4	92.7	-	-	-		-	-	-
	Cotton gin	-	-	-	1.641E4	2.330E3	85.8	-	-	-	-	-	-		-	-	-

Note: Averages account for missing data.
* Bad data.

where gaseous pollutants occur along with particulates. The scrubbers tested do not appear to be very efficient in removing submicron particles. Novel scrubbers tested thus far exhibit superior collection performance as compared to conventional scrubbers.

SECTION 7

ASSESSMENT OF CURRENT LEVEL OF FINE PARTICULATE EMISSIONS

The quantity of particulate emitted from a source to the atmosphere depends upon whether the source is controlled or uncontrolled, the type of control device(s) used, and the percentage of time the control device(s) is (are) in operation when the source is in operation.

All of the FPEIS data were obtained on controlled sources. Furthermore, almost all of the data were obtained with inertial impactors.

The present FPEIS data classified according to source type and control device type are shown in Table 6 (page 31). As has been pointed out, there are many data gaps, and a comprehensive assessment of the level of fine particulate emissions is difficult. However, some general conclusions can be drawn from the available data.

The inlet and outlet average total mass concentrations of each source/control device type are shown in Table 7. Here, one can see that the inlet mass concentration averages are of the order of 10^6 μg/dnm^3, and the outlet mass concentration averages are of the order of 10^4 μg/dnm^3. Nonferrous plants tested have relatively low inlet mass concentrations and relatively high outlet mass concentrations. Particulates emitted from these sources are predominantly submicrometer in size, and their removal with conventional devices is difficult. Chemical processes form particulates varying widely in particle size depending upon input materials and reaction conditions.

Figures in Appendix A summarize all the FPEIS data. For each test series, all the inlet particle size distributions ($\Delta M/\Delta \log D_{ae}$ versus $\log D_{ae}$) are plotted on one figure, and all the outlet particle size distributions are plotted on another figure. Since this type of graphical display is rather new, information regarding construction and interpretation is given at the beginning of Appendix A.

In Appendix A, figures showing particle size distributions are arranged in the order of their test series. However, arranging the inlet plots according to the source type shows the general characteristics of each source type. Coal-fired power boilers and coal-fired industrial boilers are characterized by predominantly large particulates and high total mass concentration. Oil-fired boilers on the other hand are characterized by relatively low mass concentration and a peak in the mass distribution function between 1 and 10 μm particle diameter.

Metallurgical operations are generally characterized by particles predominantly in the submicrometer range. Their mass distribution function peaks around 1 μm.

Asphalt aggregate drying generates very coarse particulate because of mechanical attrition of the rock within the dryer.

The particle size distributions at the outlets depend upon the source and control device(s) used. Conventional control devices are generally effective in removing the coarse particles and ineffective in removing the submicrometer particles. Therefore, the particle distributions at the outlet of these devices generally tend to peak around 1 μm.

SECTION 8

ASSESSMENT OF CURRENT FPEIS DATA BASE

The present FPEIS data classified according to source type and control device type have been shown in Table 6. There are a total of 717 runs. Nearly half of the runs pertain to coal-fired boilers. Almost all of the present data were collected with inertial impactors. The quality of particle size distributions was discussed in Section 5.

Inadequacies in nearly every aspect of the reported data severely restrict the accuracy as well as the comprehensiveness of the data base. Major deficiencies are:

- Information such as process operating conditions, and control equipment description is missing in many test reports.
- Most test reports do not have any information on the sampling location, except that it is the inlet or outlet of the control device.
- The particle physical properties such as particle density and resistivity are important parameters of aerosols. These are not available in many instances.
- The particle bioassay data are presently nonexistent.
- Information on the chemical composition of the particulates as a function of the particle size is very limited in scope. For most sources of interest, data are nonexistent.
- There are at present no standard procedures for particle sizing in process streams. Many subjective judgments are involved in making measurements.
- Impactors used in collecting the data are frequently not calibrated.

In summary, the current FPEIS data base contains limited data on some important source/collector combinations. The quality of data is generally as good as the state of the art of source testing.

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

A computerized Fine Particulate Emissions Information System has been developed. At the present time, only a limited quantity of data exists in the data base. Because of inadequate data, an accurate and comprehensive survey of the applicability and effectiveness of particulate control technology, and an assessment of the current level of fine particulate emissions could not be made. However, the available data are adequate to make a preliminary study of some important source/collector combinations.

The present data indicate that the inlet mass concentration averages are of the order of 10^6 $\mu g/dnm^3$, and the outlet mass concentration averages are of the order of 10^4 $\mu g/dnm^3$. Particle size distribution data indicate that for coal-fired boilers the particle sizes are distributed over a wide range, with most of the mass associated with large particles. Oil-fired boilers, and metallurgical plants emit significant amounts of fine particulates. Asphalt aggregate drying generates a very high concentration of coarse aerosol. Chemical processes form particles whose size depends on the feed material and reactions involved.

The principal recommendations for improving the quality of the data base are:

1. Active data acquisition effort should continue with updates to the data base being made on a regular basis.

2. Encourage source testing groups to review their data as contained in the FPEIS and complete missing data elements to the extent possible.

3. Obtain and analyze user requests, requirements, problems, and input.

4. Continue improvement of data input sheets.

5. Distribute FPEIS Data Input Forms to source testing groups and urge their usage. Use of the forms will minimize data coding errors and reduce the delay between data generation and data entry into the FPEIS.

6. Field testing on carefully selected source/collector combinations should be a major activity for the improvement of the existing data base.

7. Studies and surveys should be conducted to determine the operational reliability of various control devices so an accurate emissions inventory can be made.

8. Calibrations for the impactors used in source testing should be obtained.

Table 8. CONVERSION FACTORS

Metric unit	Multiply by	To obtain English equivalent
Atmospheres	2.992×10^{1}	in. Hg (at 0°C)
C	(c x 9/5) + 32	F
cc	6.102×10^{-2}	$in.^{3}$
cm^{2}	1.550×10^{-1}	sq in.
Jueles	9.486×10^{-4}	Btu
kg/m^{3}	6.243×10^{-2}	lb/ft^{3}
kg-cal	4.186	kJ
kg-m	9.296×10^{-3}	Btu
km	6.214×10^{-1}	miles (statute)
kw	5.692×10^{1}	Btu/min
kw-hr	3.6×10^{6}	J
liters	3.531×10^{-2}	ft^{3}
liters/min	5.886×10^{-4}	ft^{3}/sec
m	3.281	ft
m/min	5.468×10^{-2}	ft/sec
mg	1.5432×10^{-2}	grains
mm	3.937×10^{-2}	in.
m^{2}	1.076×10^{1}	sq ft
tons (metric)	2.205×10^{3}	pounds
w	3.4129	Btu/hr

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APPENDIX A

SUMMARY OF PARTICLE SIZE DISTRIBUTION PLOTS

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The standard output of the FPEIS includes a plot of particle size distribution data for each test subseries. In this plot, the mass ($\Delta M/\Delta \log D_{ae}$), surface ($\Delta S/\Delta \log D_{ae}$), and number ($\Delta N/\Delta \log D_{ae}$) distributions are plotted as a function of particle aerodynamic diameter, D_{ae}. However, for the purpose of summarizing the FPEIS data for each test series, all the inlet mass distributions are plotted on one page, and all the outlet mass distributions are plotted on another page. The following discussion will be helpful in the interpretation of the summary plots.

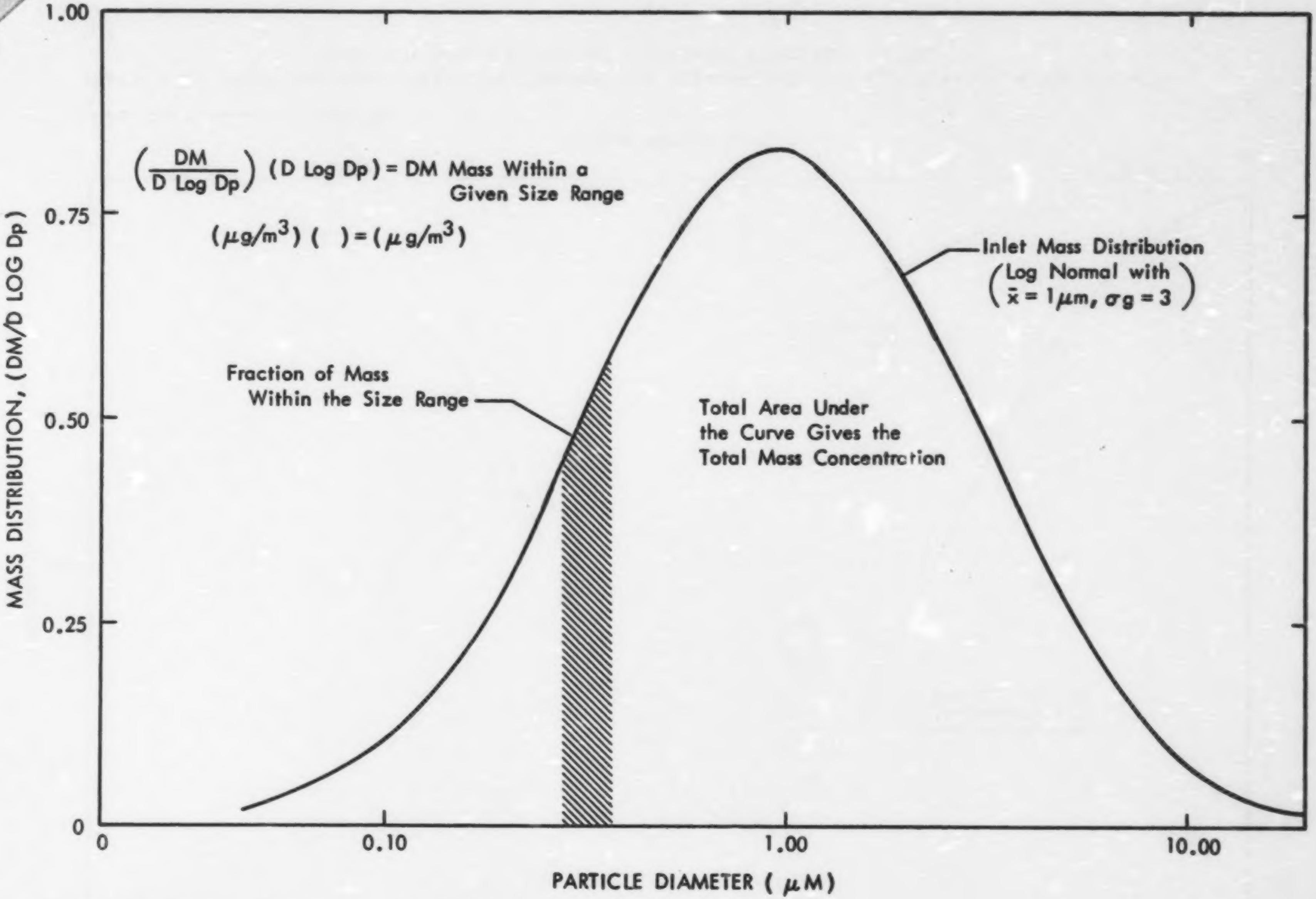
Figure A-1 shows a lognormal inlet mass distribution ($\bar{x} = 1$ µm; $\sigma_g = 3$) of a hypothetical source/collector combination. The quantity of interest is mass per unit volume within a size range. Since the particle size ranges over four decades, we have to use a $\log_{10}$ scale on the abscissa. Furthermore, as there is no mass concentration associated with a given size, we need to select $\Delta M/\Delta \log D_{ae}$ on the ordinate as suggested by the following equation.

$$\left(\frac{\Delta M}{\Delta \log_{10} D_{ae}}\right)\left(\Delta \log_{10} D_{ae}\right) = \Delta M \quad \text{Mass within a given size range}$$

If we divide the above equation by total mass concentration, the right-hand side then represents the fraction of mass within a given size range, and the distribution function density ($\Delta M/\Delta \log D_{ae}$) becomes dimensionless. By plotting $\Delta M/\Delta \log D_{ae}$ on a linear scale and D_p on a log scale, the area under the curve represents the fraction of mass within any size range. The mode or the mean of this curve as well as the percentage mass within a given size range can be visually estimated and easily interpreted, which is the primary purpose of such graphs.

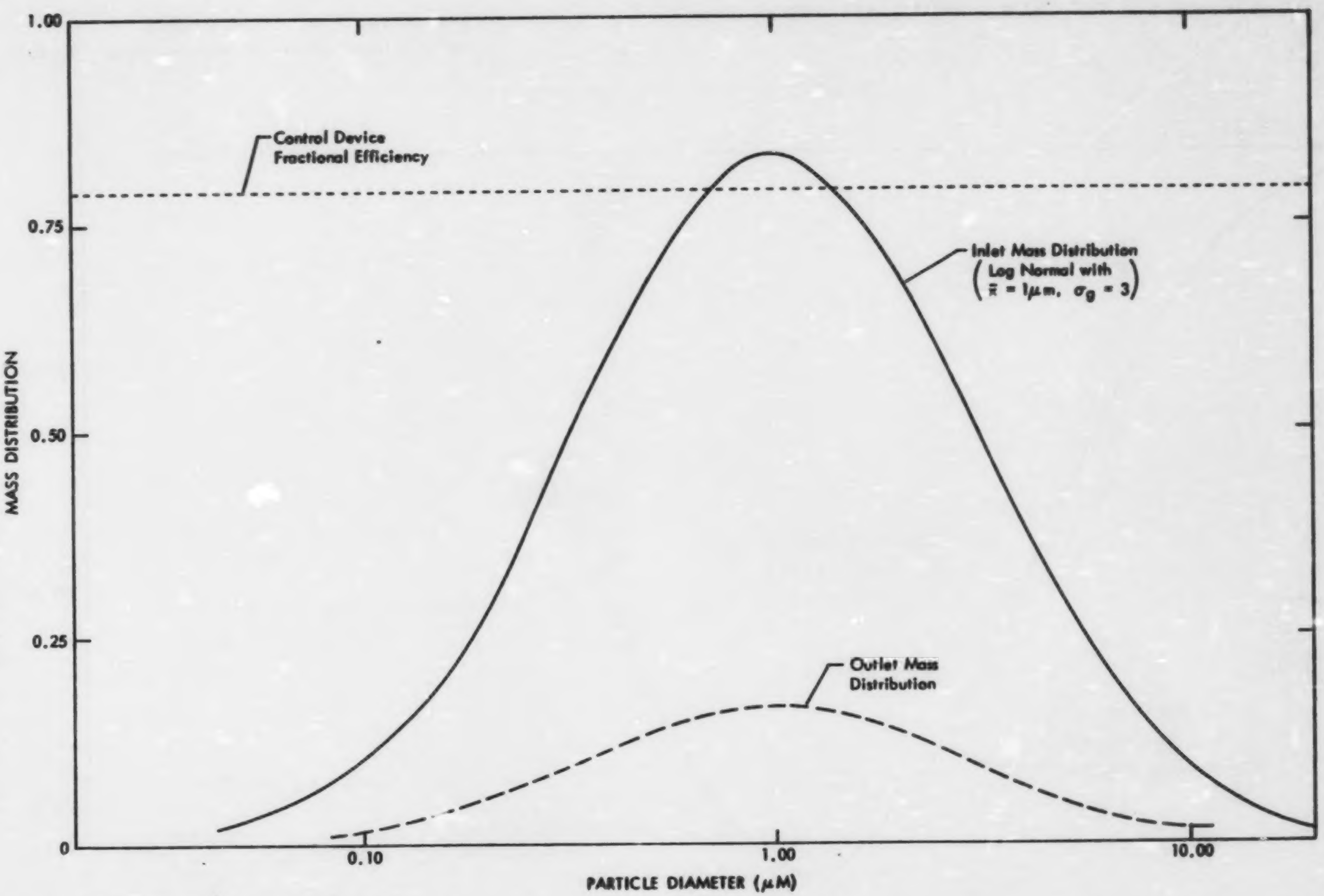
Another useful feature of the present plots results from normalization of ordinate $\Delta M/\Delta \log D_{ae}$ by the total mass of the distribution. If we draw inlet and outlet distributions with one scale (i.e., divide the ordinate with a constant scale factor) the outlet distribution will usually be very close to the abscissa and cannot reveal all its features. However, by choosing the total mass as the scale factor, the effect of mass concentration on the plots is eliminated, and inlet and outlet size distribution curves show only relative mass concentrations. As shown in Figure A-2, if the control device fractional efficiency is independent of particle size, the inlet and outlet particle size distribution will be the same, and normalizing ordinates with total mass concentration makes the inlet and outlet particle size distribution curves coincide. So, we find that normalized size distribution curves will coincide with each other (irrespective of total mass concentration) when their size distributions are the same, and vice versa.

For summarizing the size distribution data of each test series, all inlet mass distributions are plotted on one page, and all the outlet mass distributions are plotted on another page. However, instead of using total mass of



Scale: 1 = Total Mass Concentration ($\mu g/m^3$)

Figure A-1. Inlet Mass Distribution of a Hypothetical Source/Collector Combination

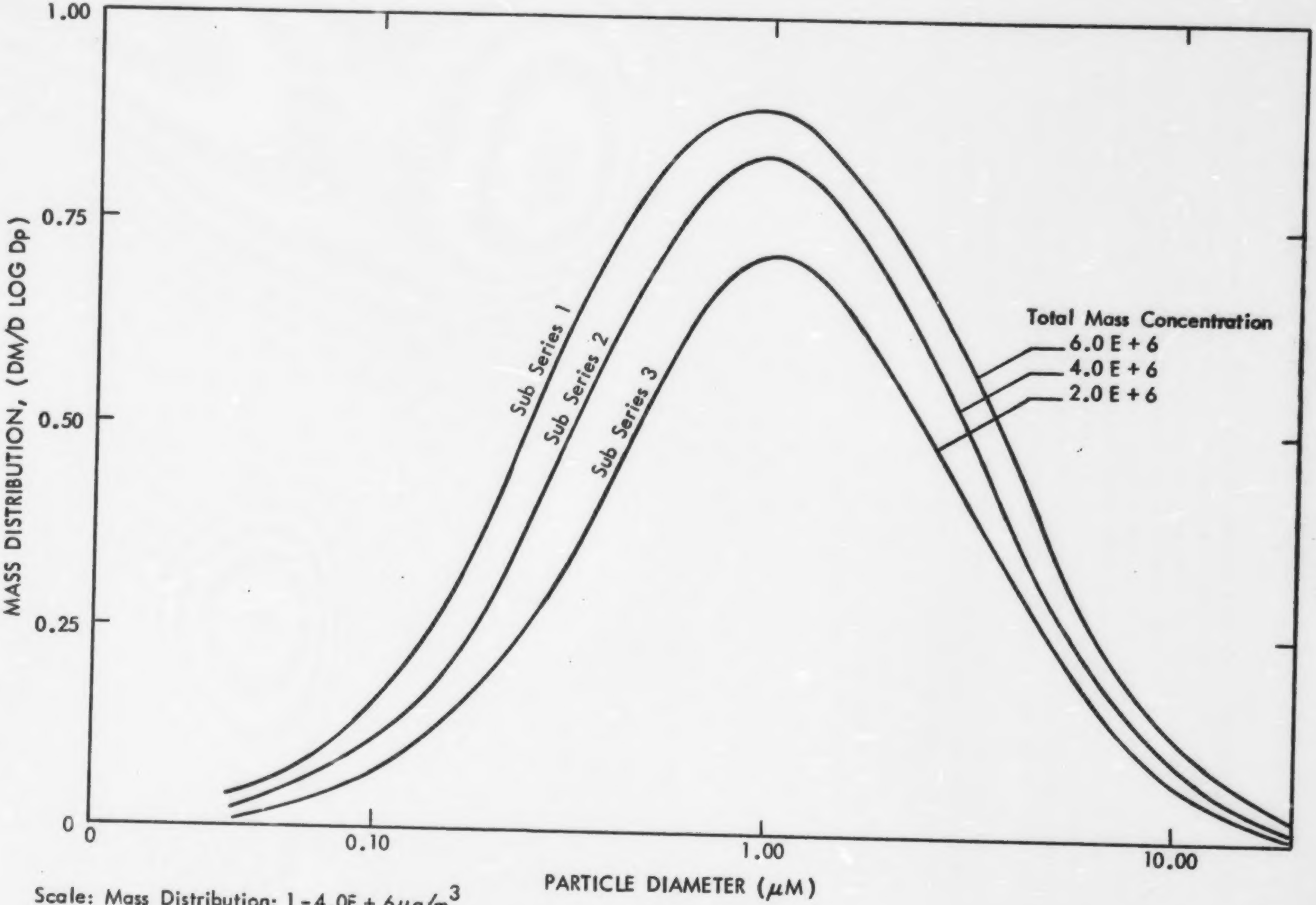


Scale: Mass Distribution: 1 - 2.000E + 06

Figure A-2. Inlet and Outlet Mass Distributions of a Hypothetical Source/Collector Combination With Collector Having a Constant Fractional Efficiency of 80%

each distribution as the normalizing factor, twice the average total mass of all runs in a given test series is used. This type of plot shows variation in total mass concentration as well as size distribution. For example, Figure A-3 shows three inlet size distribution curves whose total mass concentrations are different but size distribution is the same. Notice that the shapeof the curves is similar due to same size distribution, but the three curves do not coincide with each other because of total mass concentration differences. Of course, if both size distribution and total mass concentration are different for these runs, the shape as well as the location of these curves change.

In the summary plots (Figures A-4 to A-94) the individual points and an average eye fit curve is plotted. The shape of the eye fit curve indicates the average size distribution, and the scale shows twice the average total mass concentration of all runs plotted on a given page. These curves are, of course, subject to all of the limitations of eye-fit curves. They are intended merely to show trends. Application of an appropriate analytical technique is necessary to obtain a statistically accurate curve if detailed evaluations are desired.



Scale: Mass Distribution: 1 - 4.0E + 6μg/m^3

Figure A-3. Three Inlet Mass Distributions of a Hypothetical Source/Collector Combination

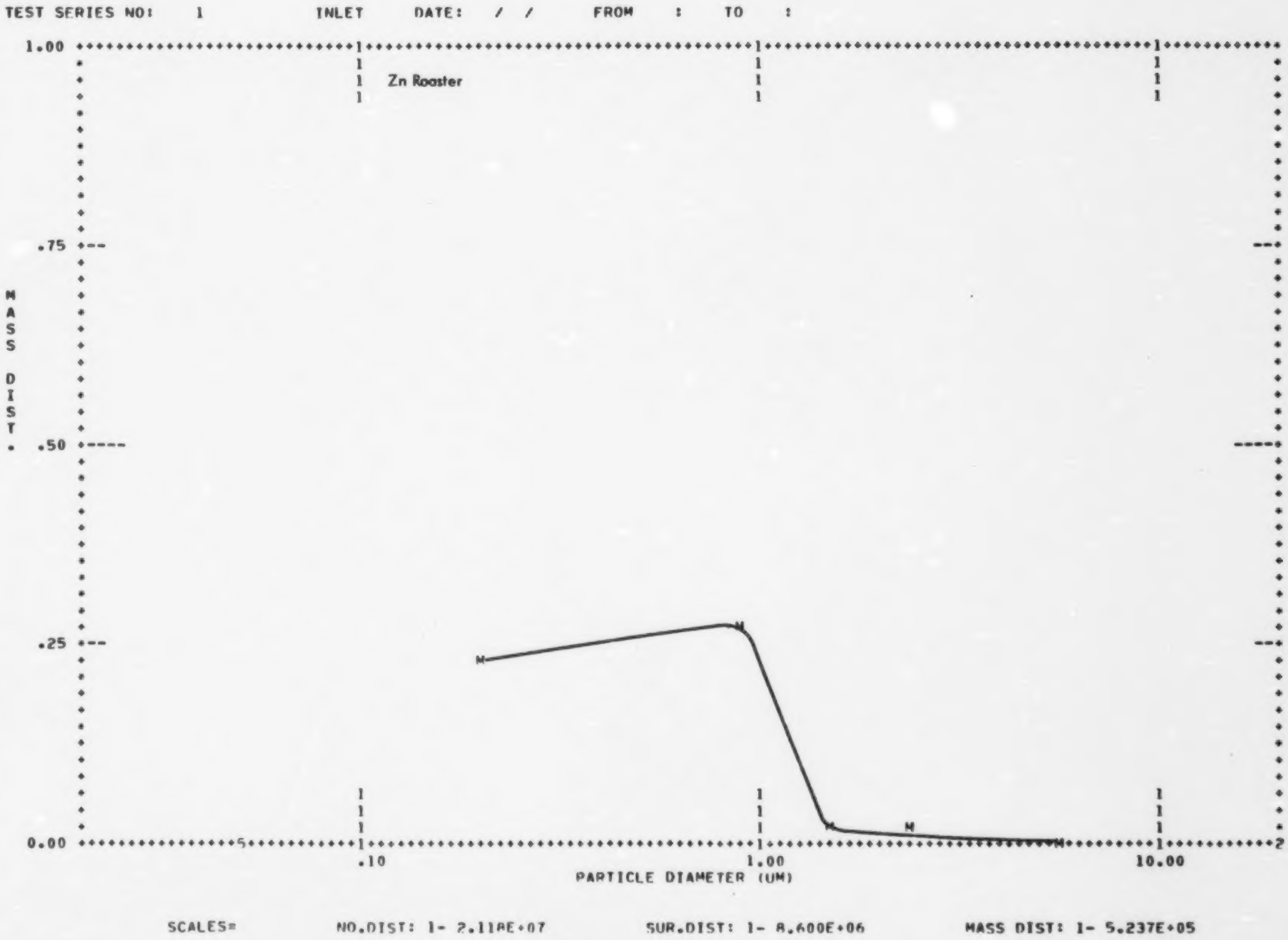


Figure A-4. Inlet Size Distributions of Test Series No. 1

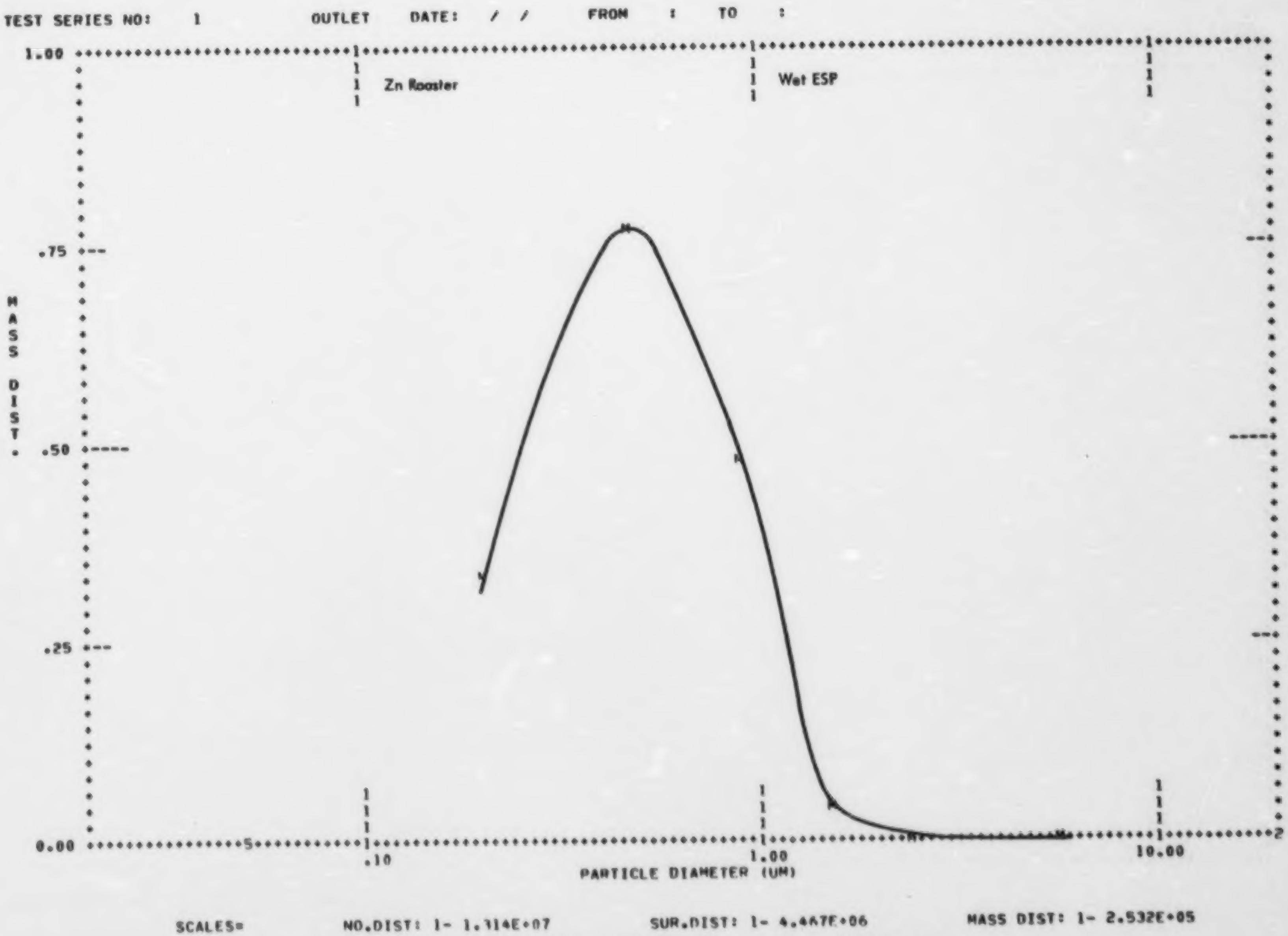


Figure A-5. Outlet Size Distribution of Test Series No. 1

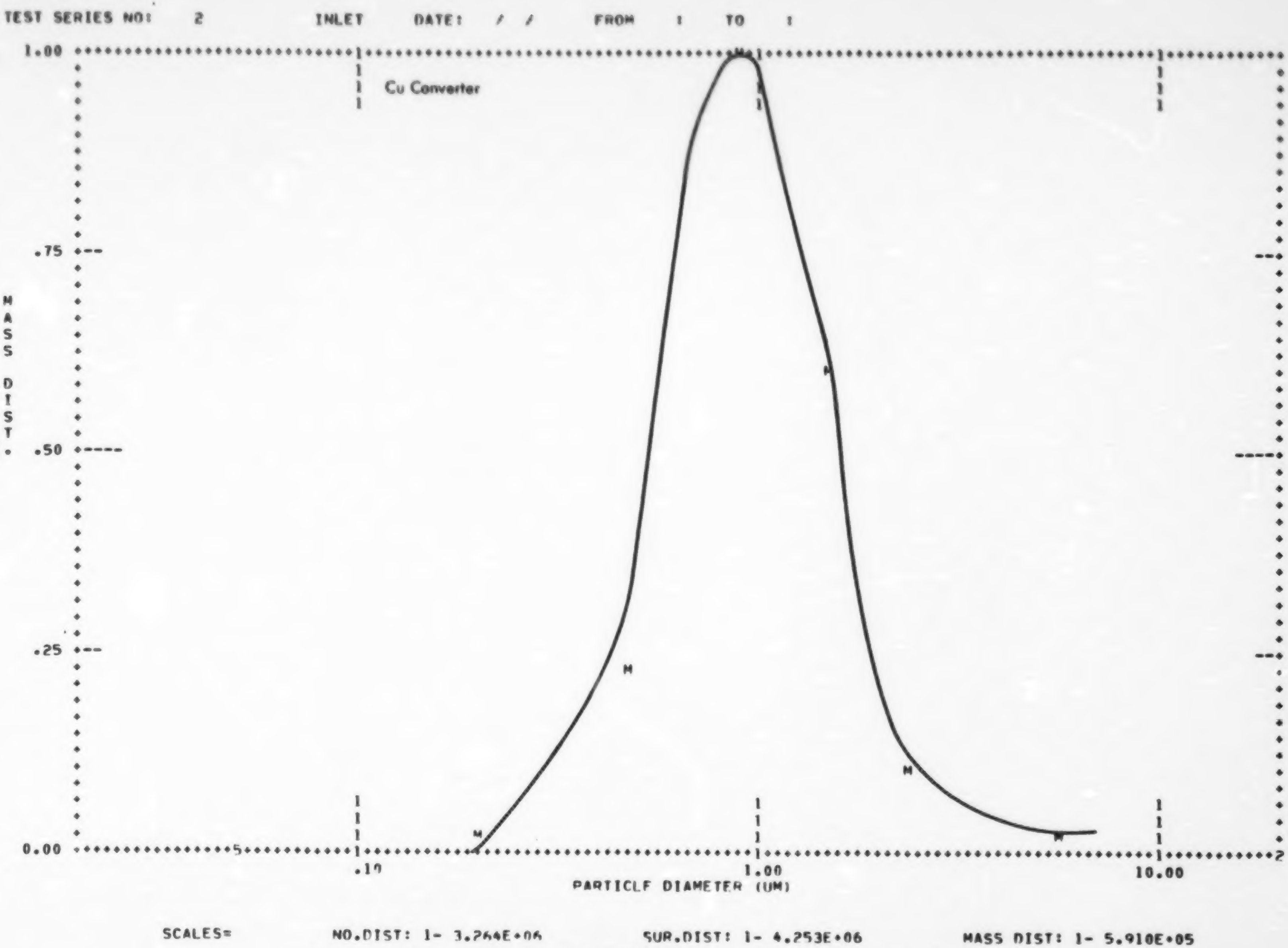


Figure A-6. Inlet Size Distribution of Test Series No. 2

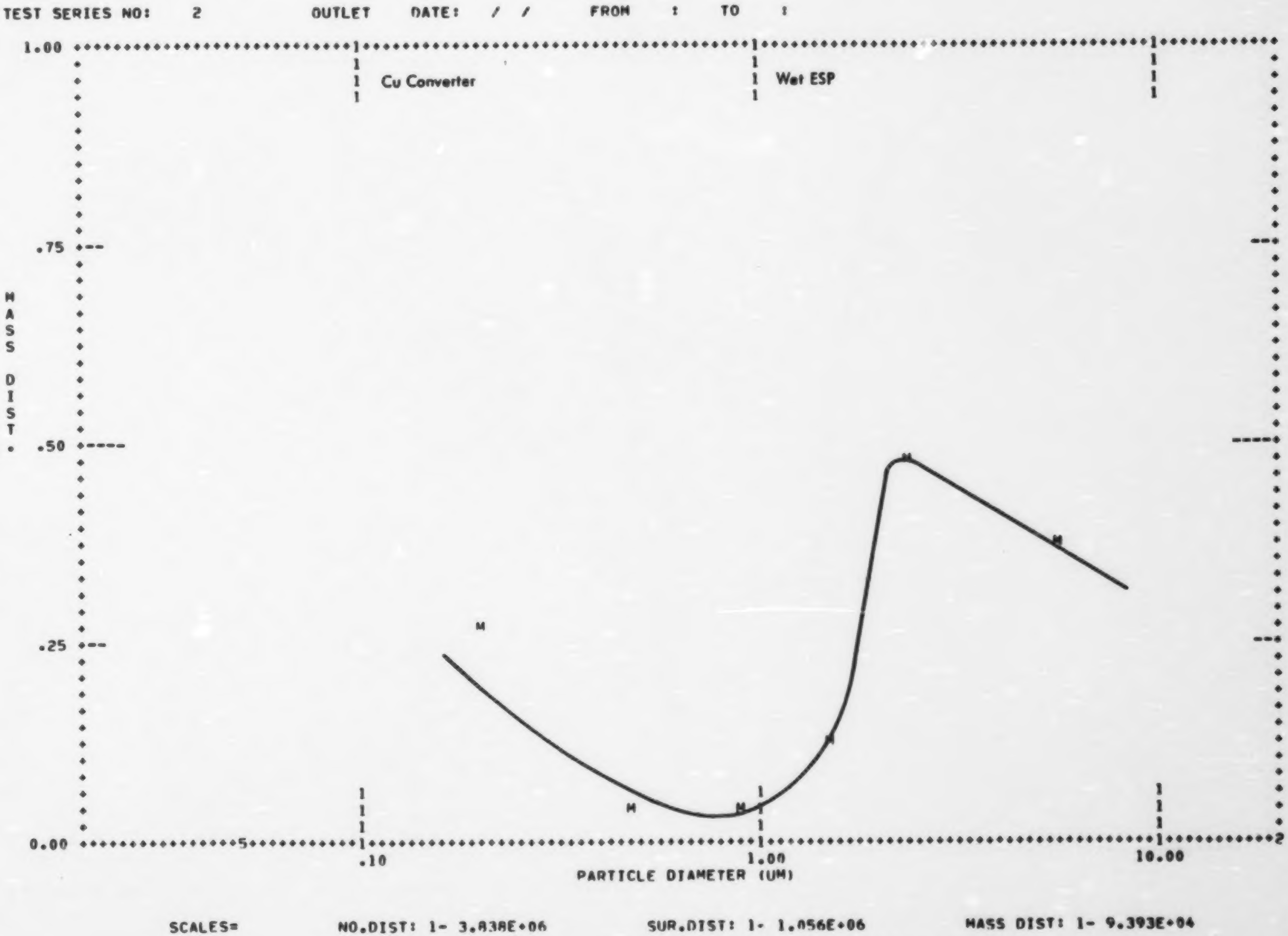


Figure A-7. Outlet Size Distribution of Test Series No. 2

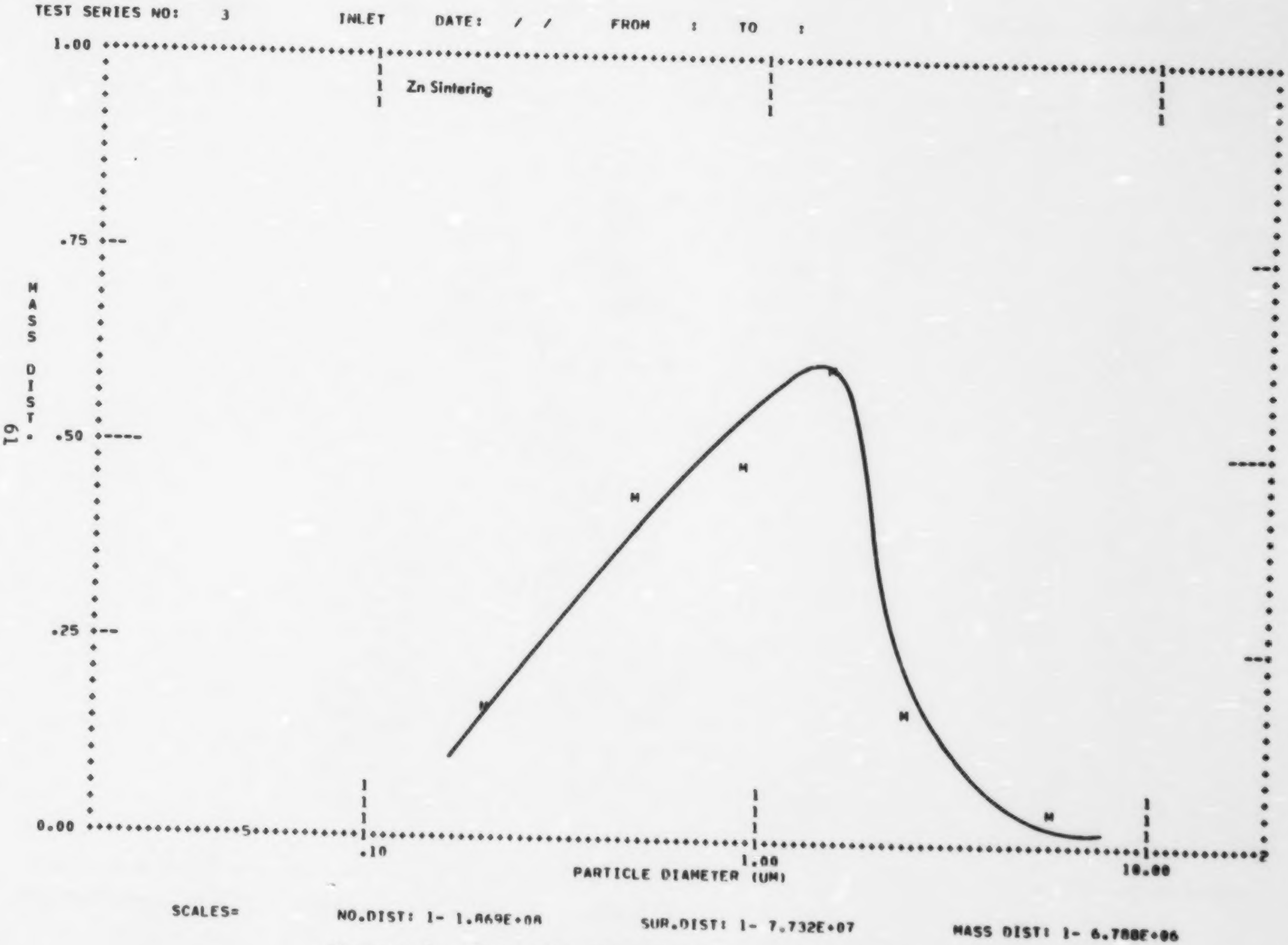


Figure A-8. Inlet Size Distribution of Test Series No. 3

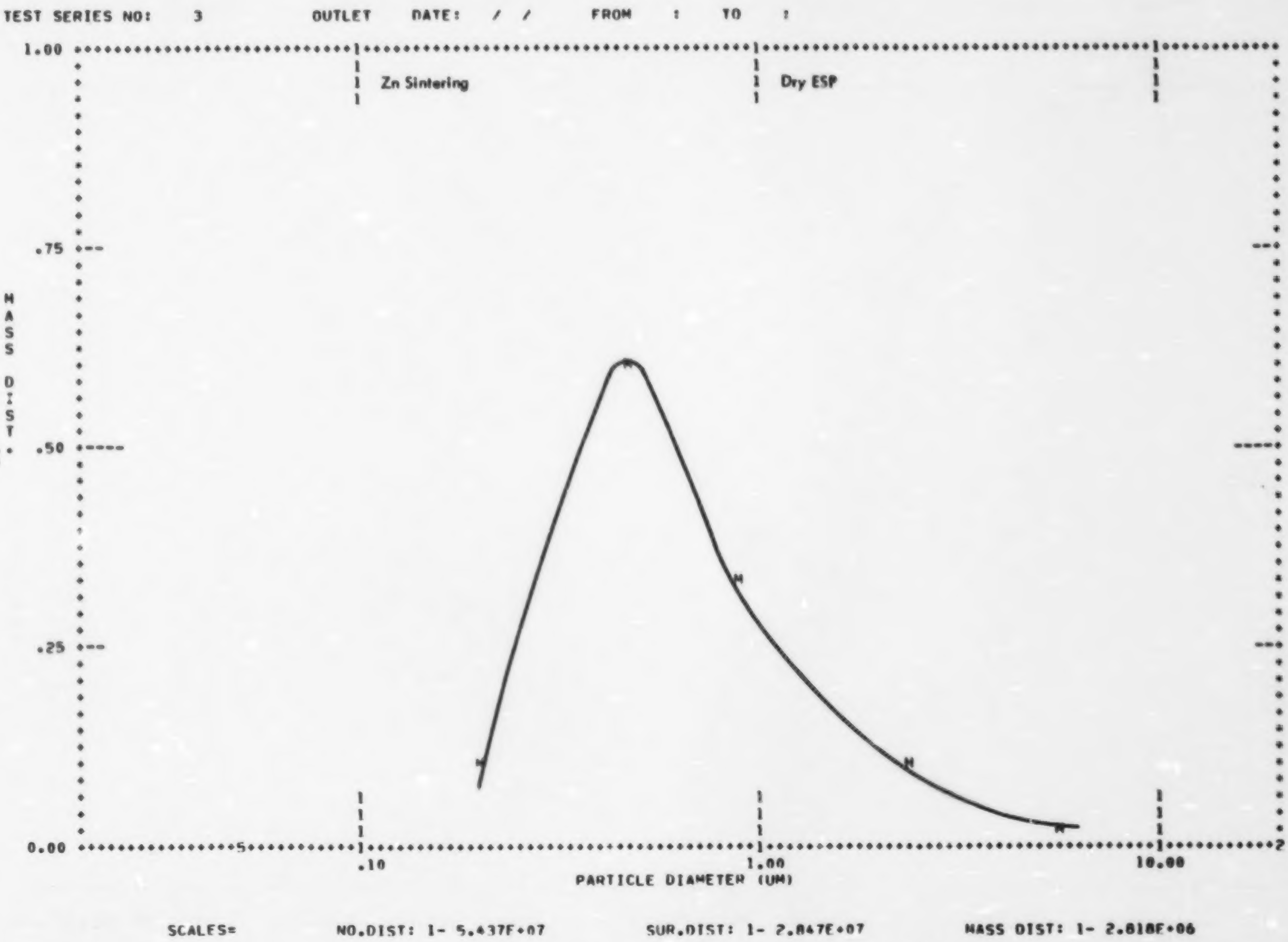


Figure A-9. Outlet Size Distribution of Test Series No. 3

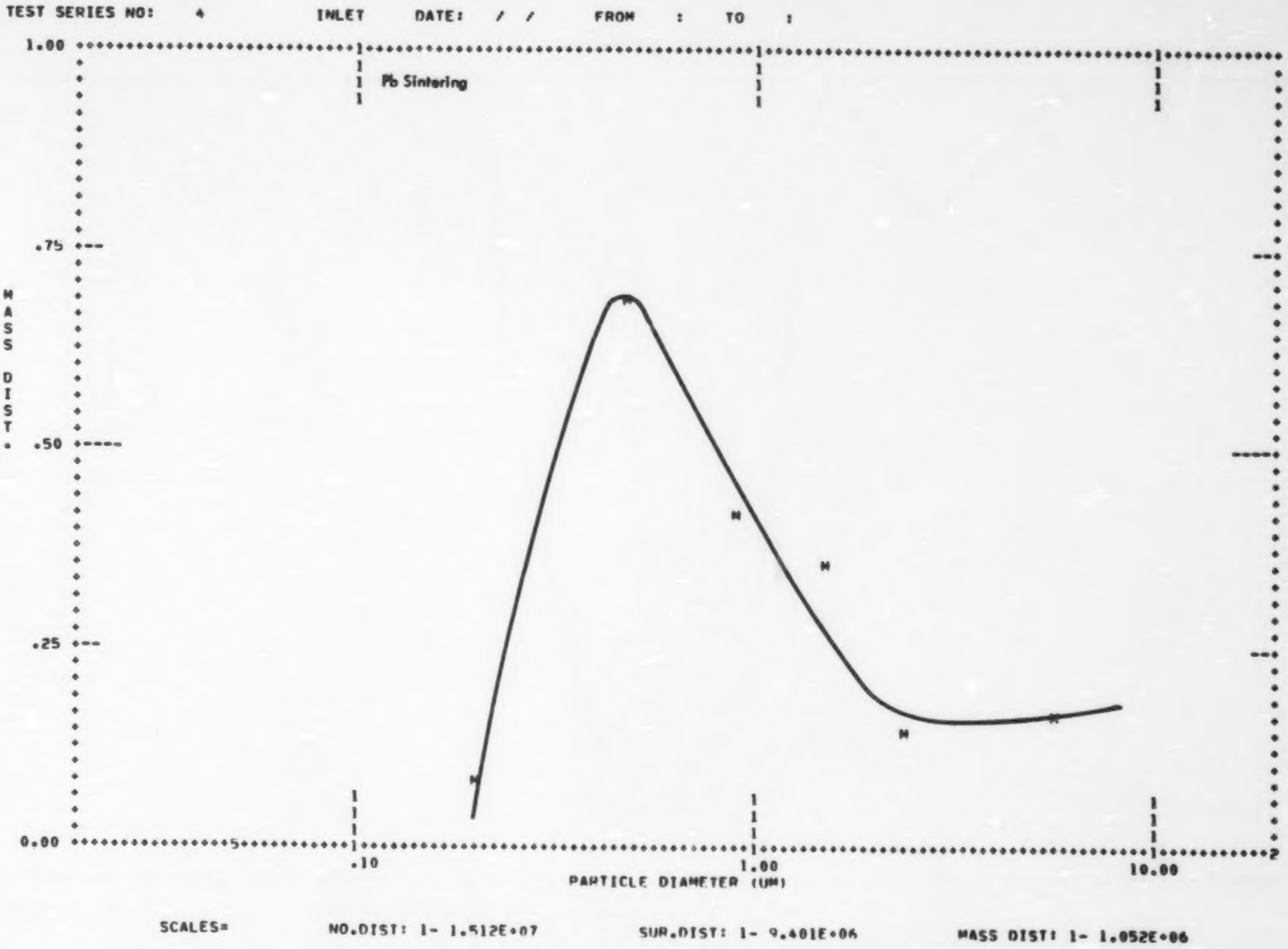


Figure A-10. Inlet Size Distributions of Test Series No. 4

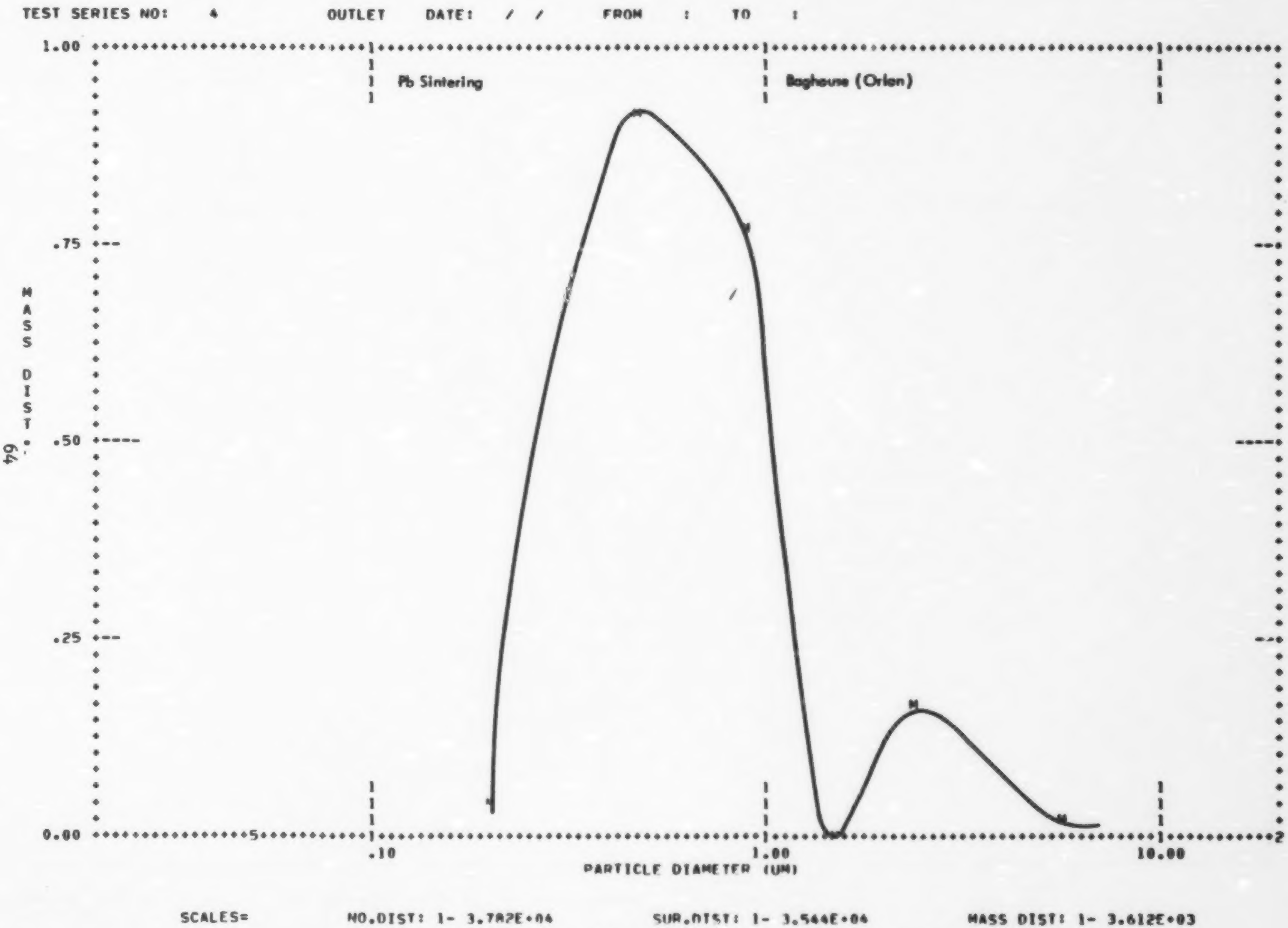


Figure A-11. Outlet Size Distributions of Test Series No. 4

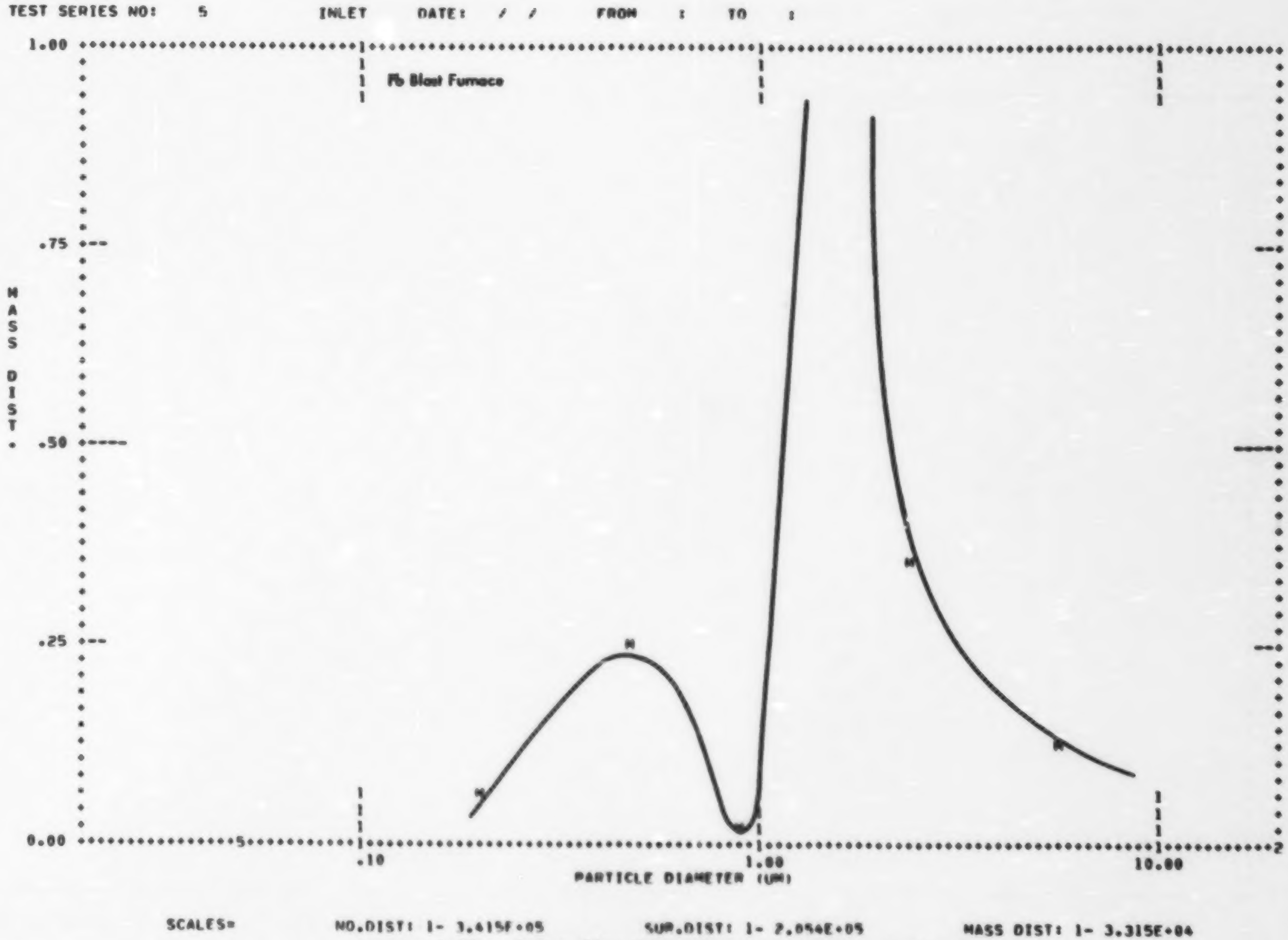


Figure A-12. Inlet Size Distributions of Test Series No. 5

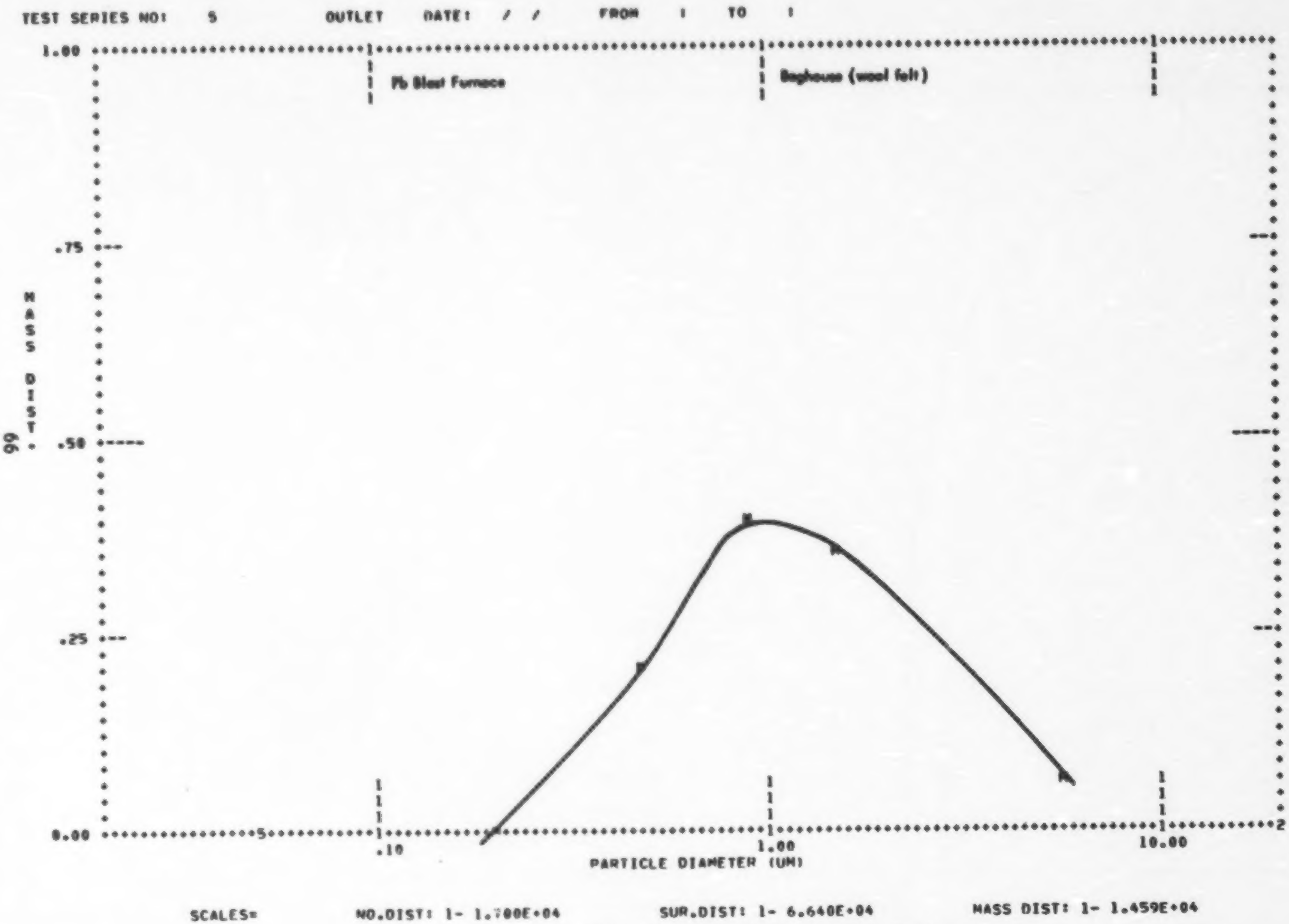


Figure A-13. Outlet Size Distributions of Test Series No. 5

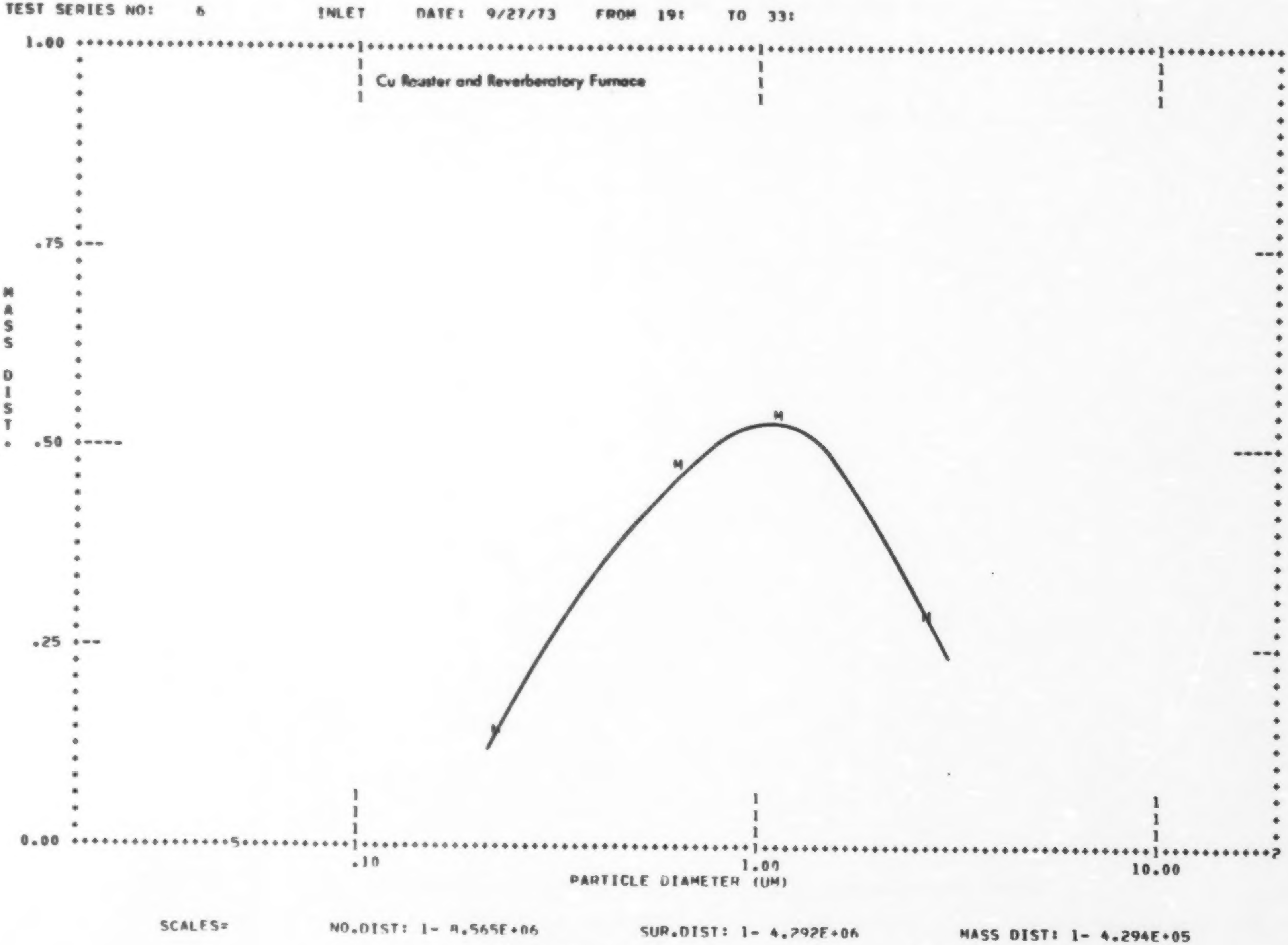
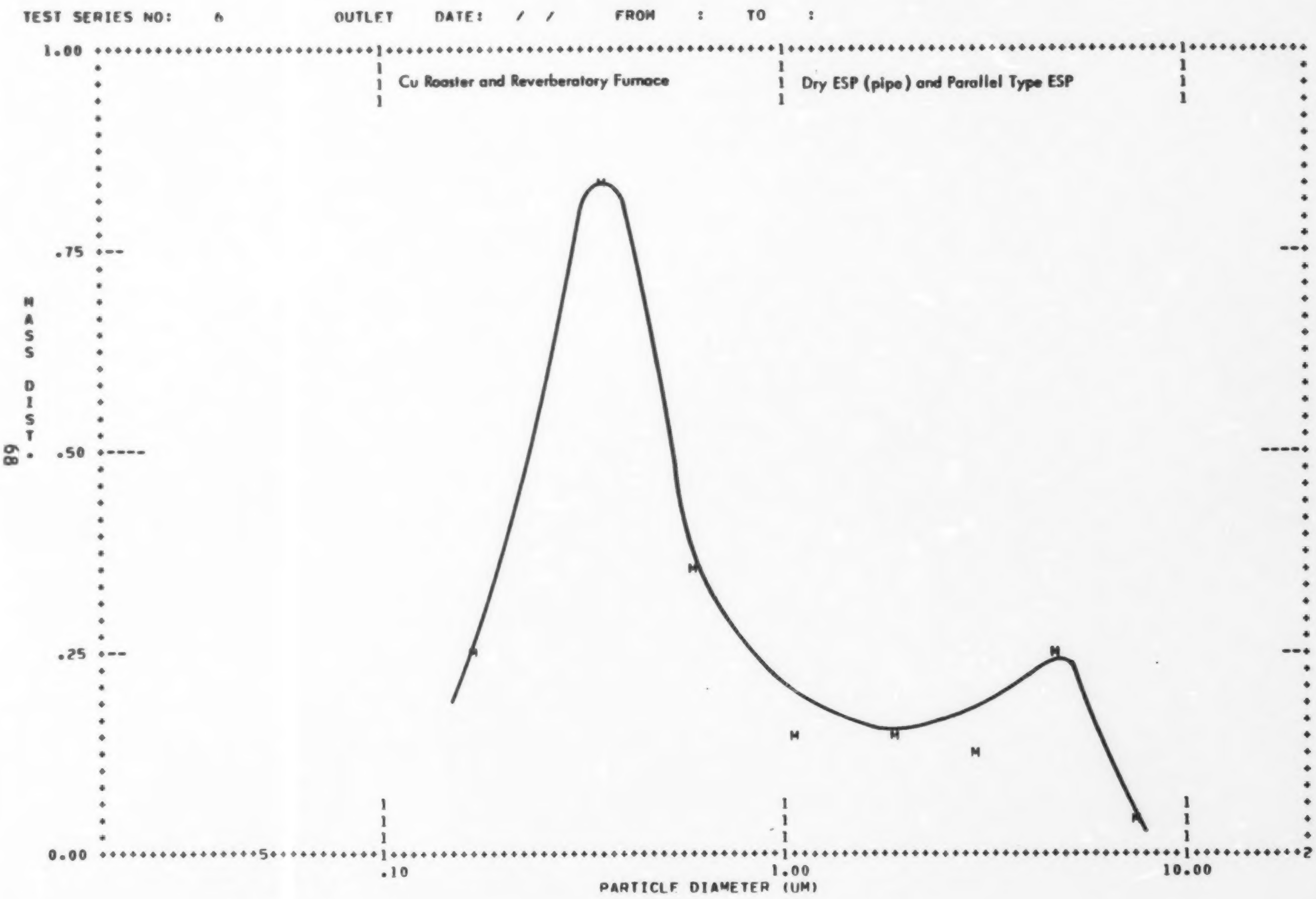


Figure A-14. Inlet Size Distributions of Test Series No. 6



SCALES= NO.DIST: 1- 2.986E+07 SUR.DIST: 1- 9.232E+06 MASS DIST: 1- 5.818E+05

Figure A-15. Outlet Size Distributions of Test Series No. 6

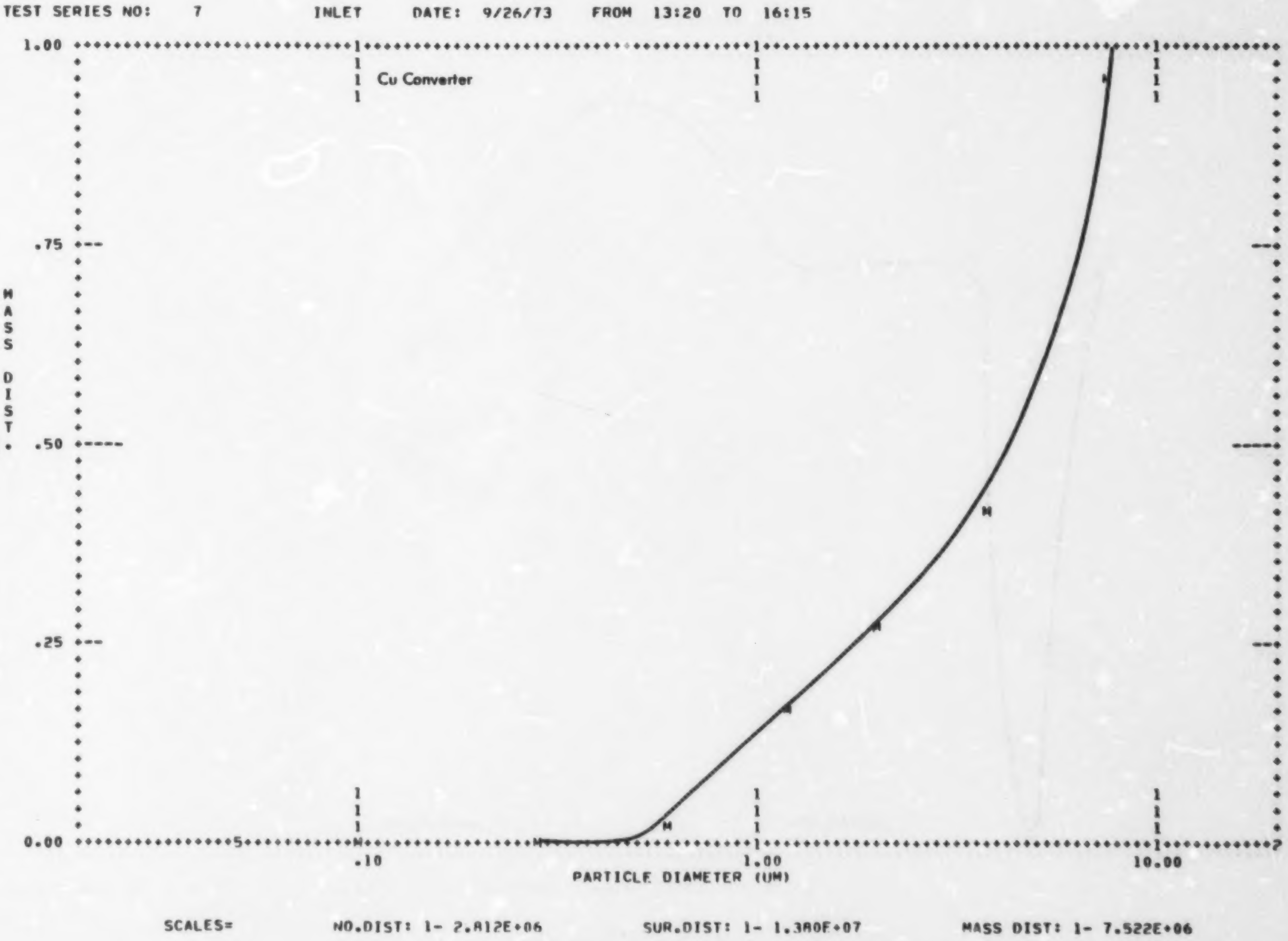


Figure A-16. Inlet Size Distributions of Test Series No. 7

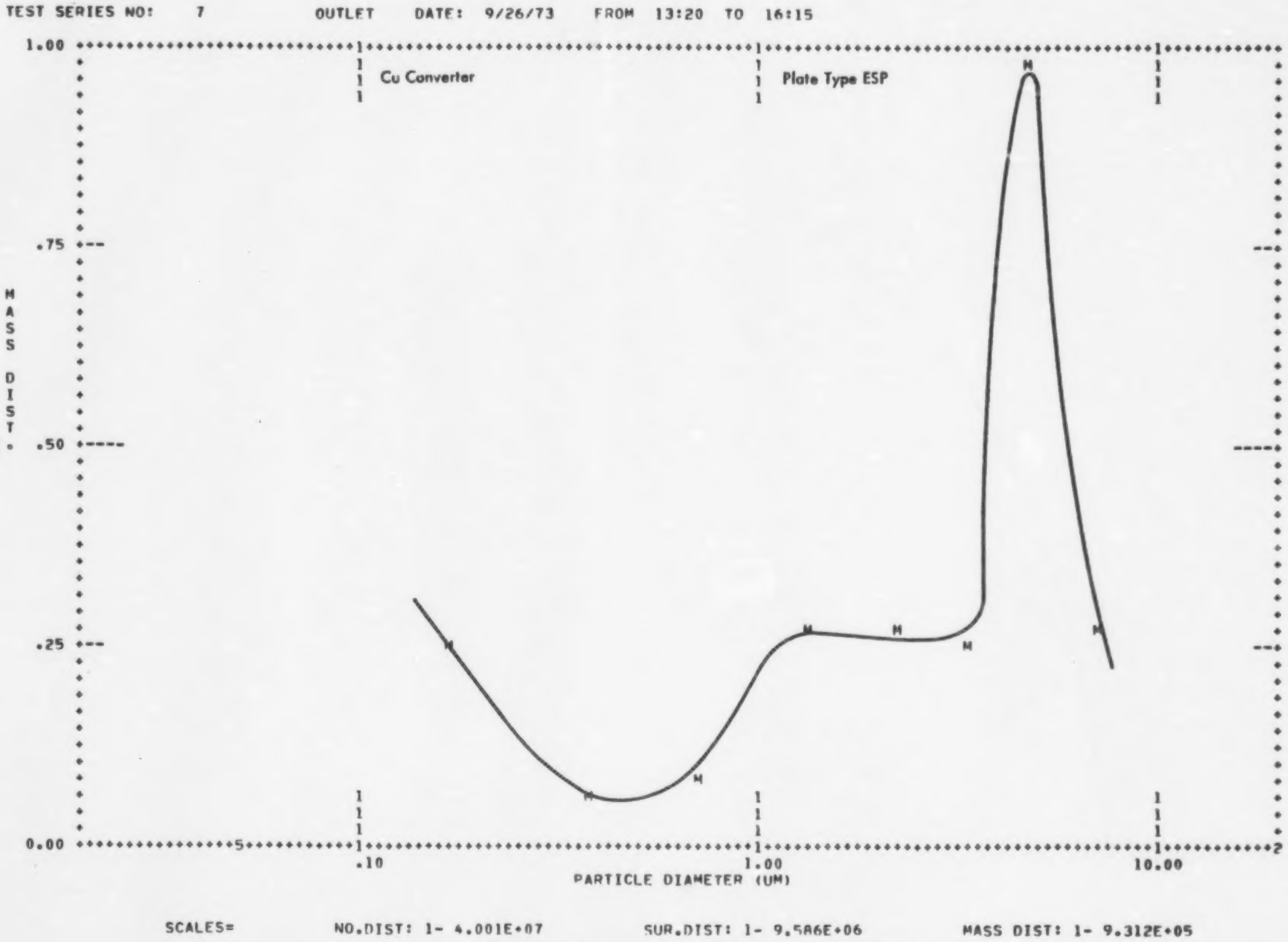


Figure A-17. Outlet Size Distributions of Test Series No. 7

TEST SERIES NO: 8 INLET DATE: 12/ 7/73 FROM : TO :

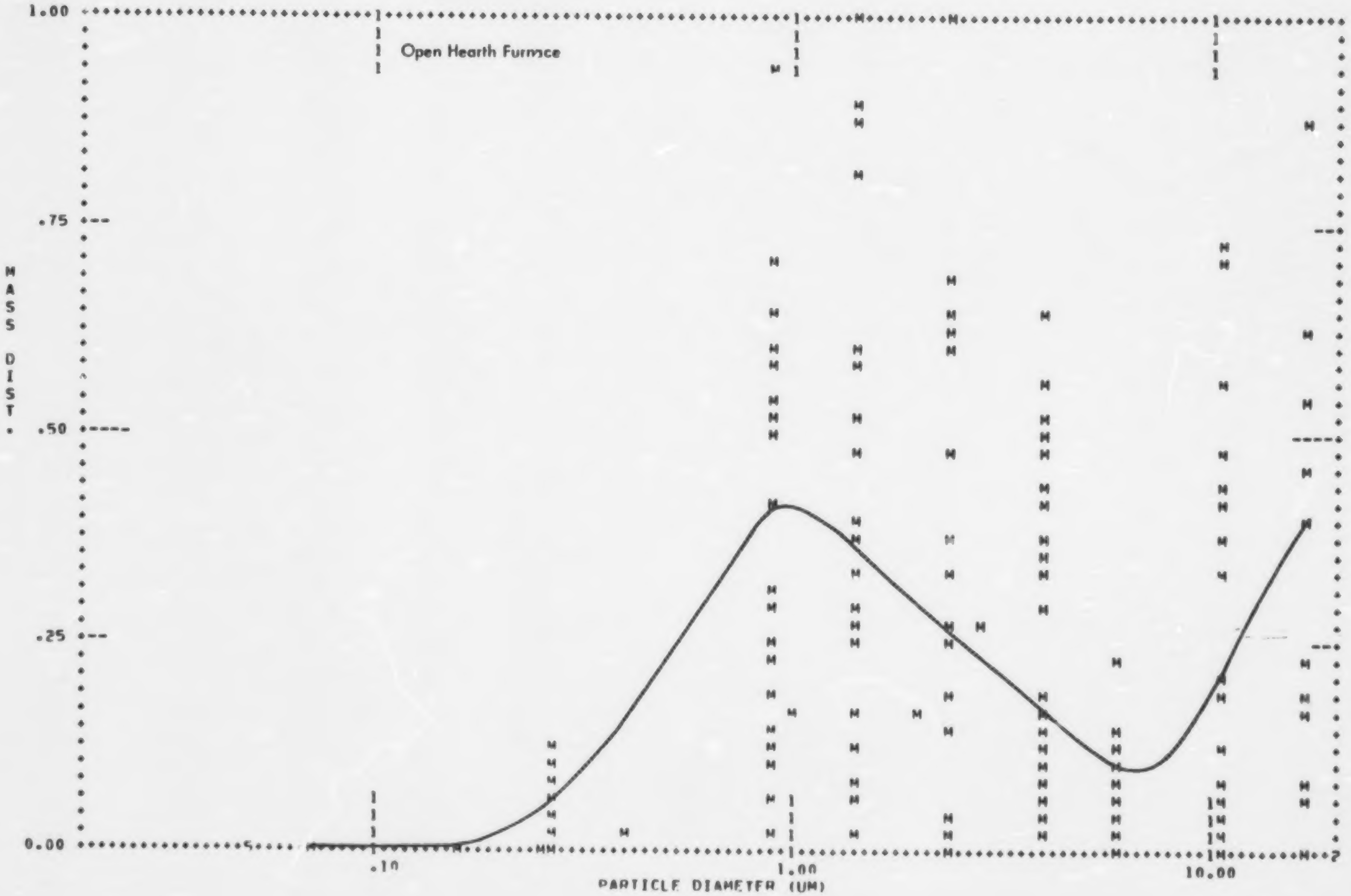


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Figure A-18. Inlet Size Distributions of Test Series No. 8

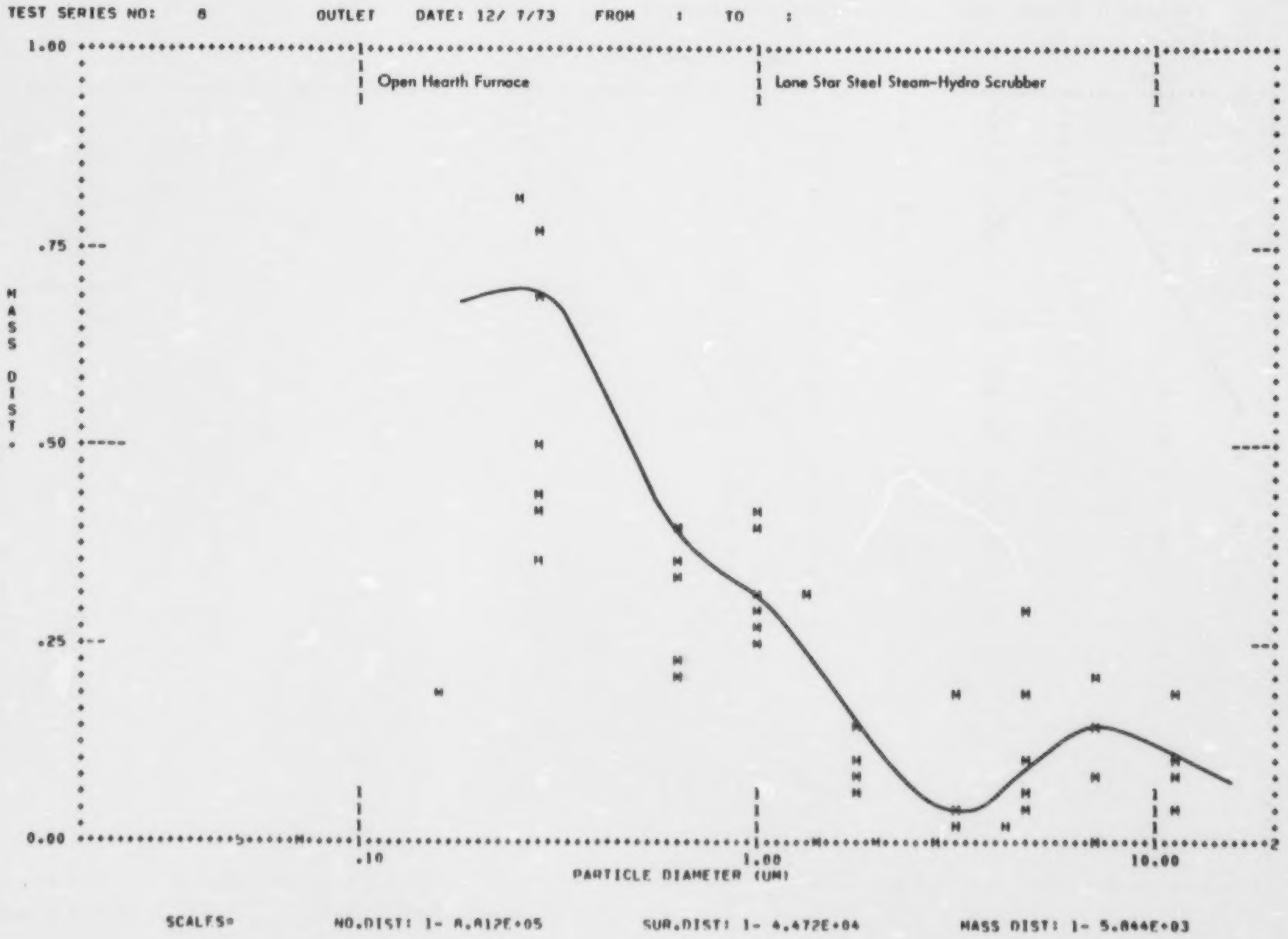


Figure A-19. Outlet Size Distributions of Test Series No. 8

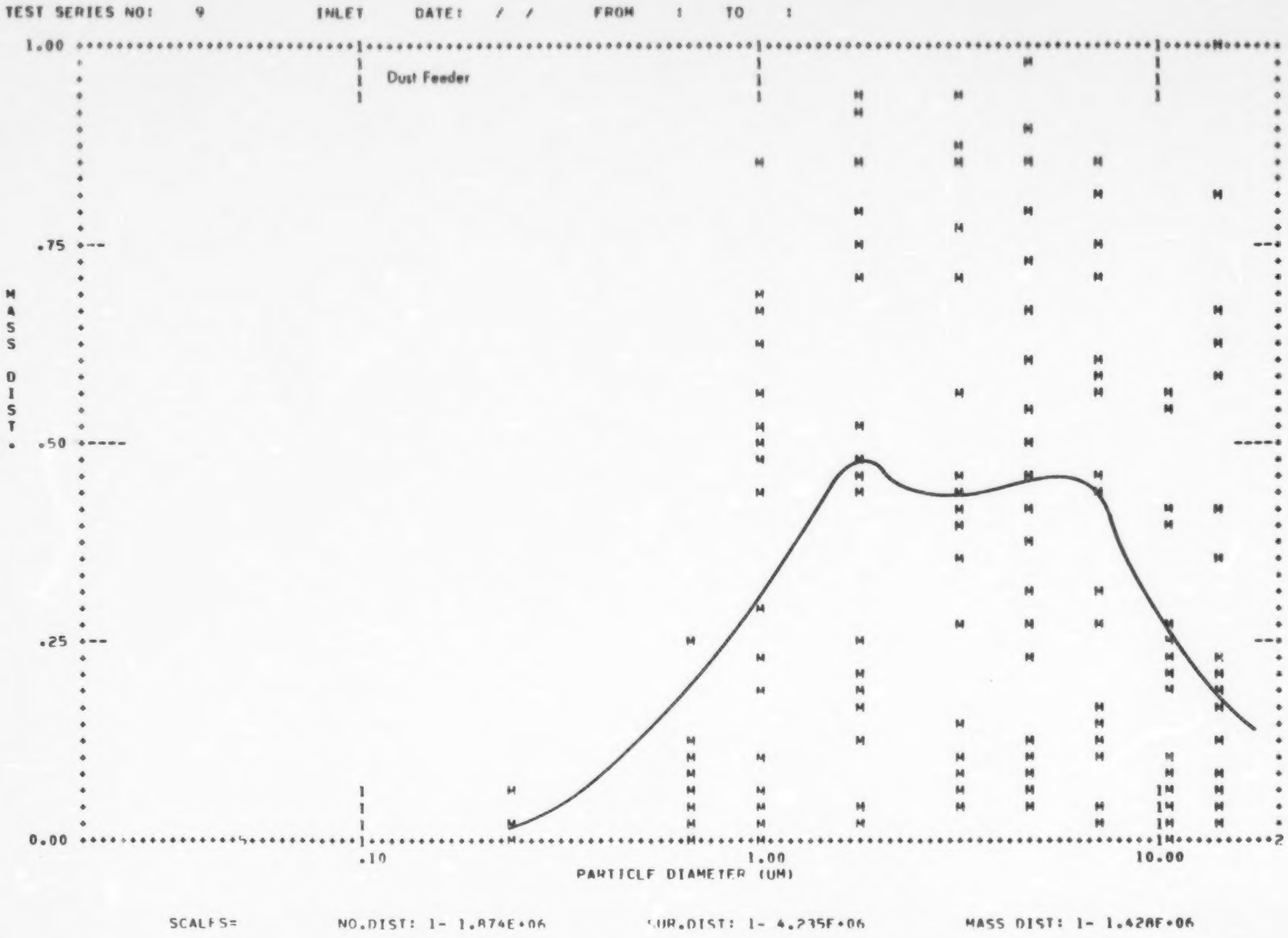


Figure A-20. Inlet Size Distributions of Test Series No. 9

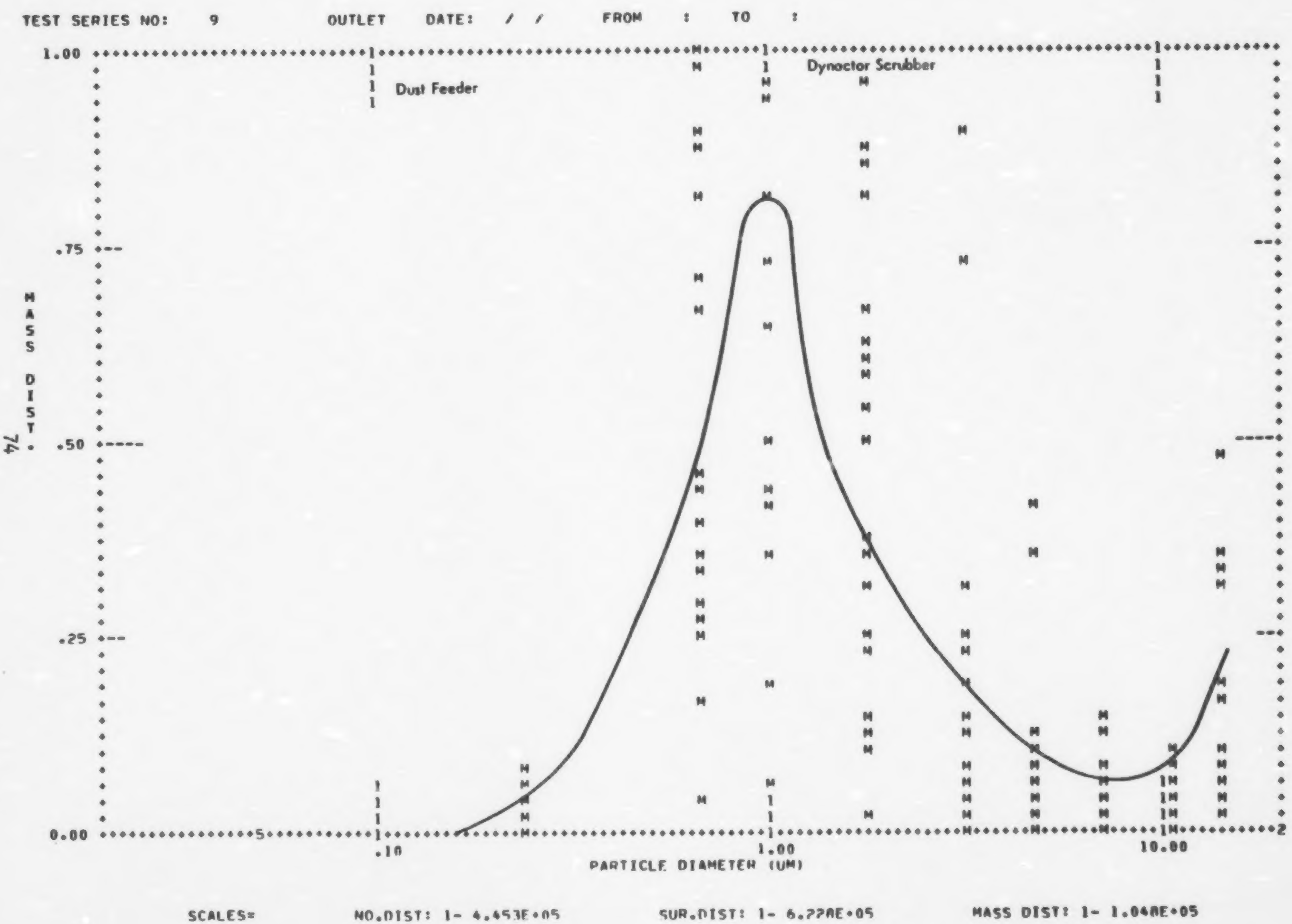


Figure A-21. Outlet Size Distributions of Test Series No. 9

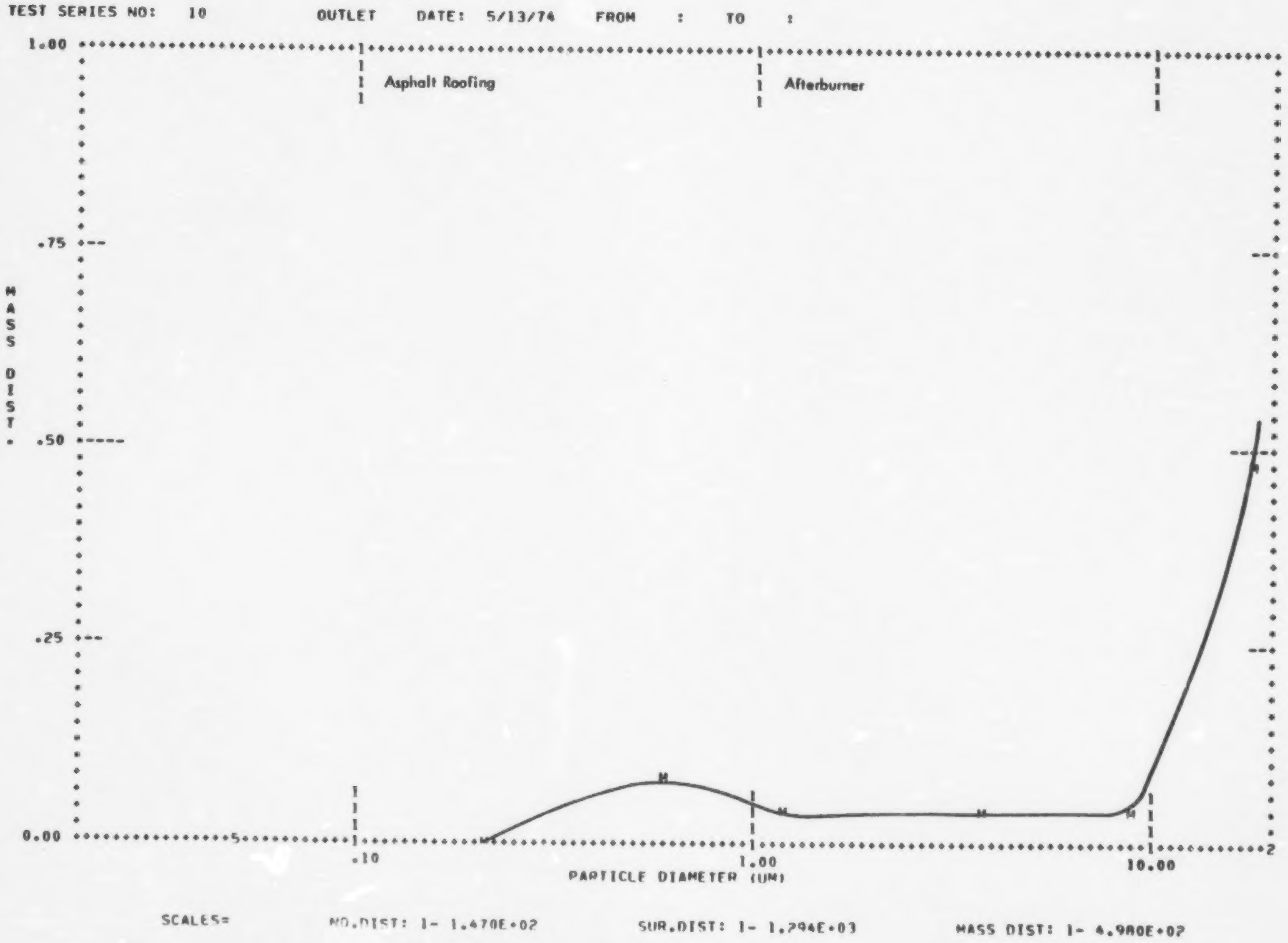


Figure A-22. Outlet Size Distributions of Test Series No. 10

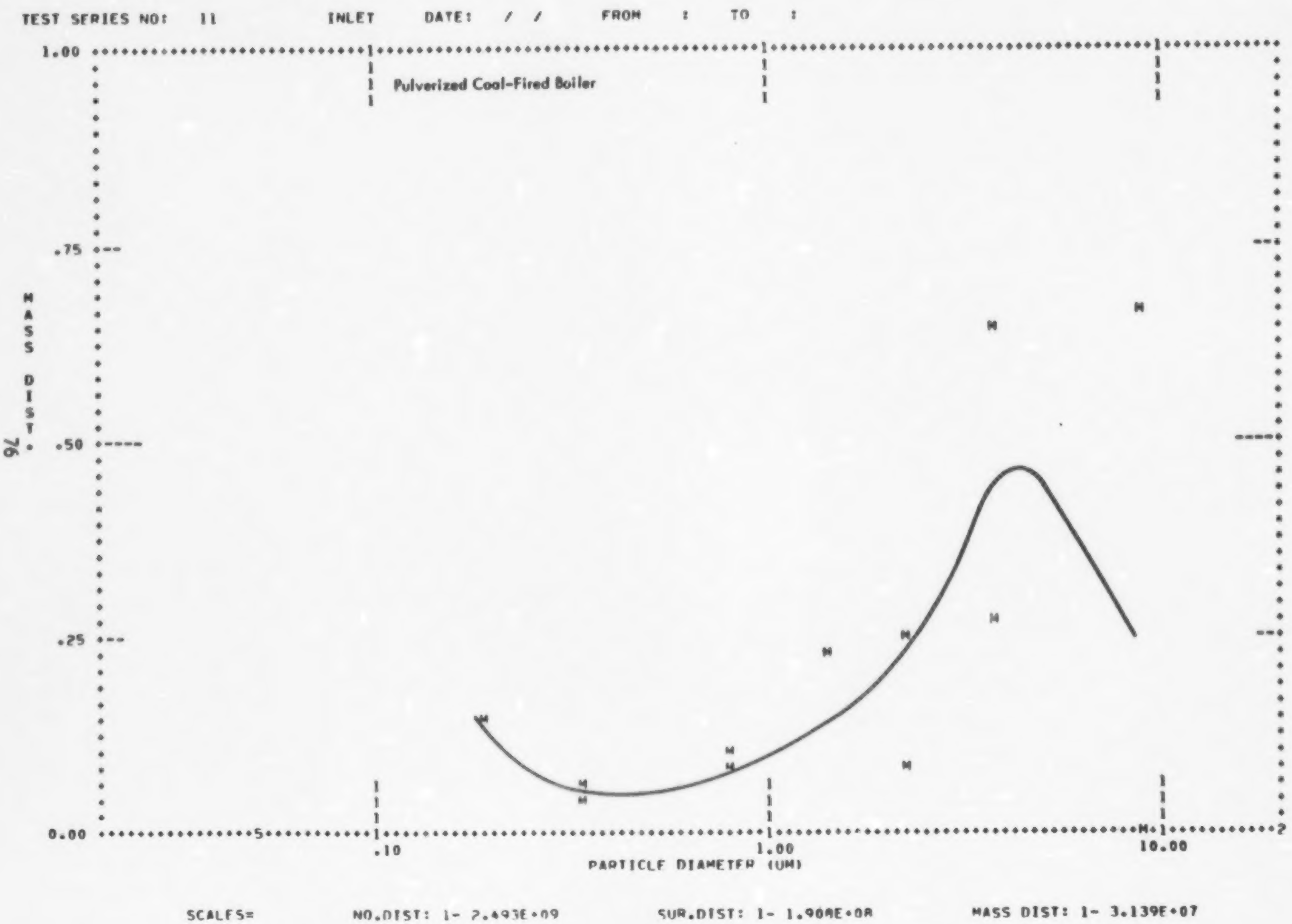


Figure A-23. Inlet Size Distributions of Test Series No. 11

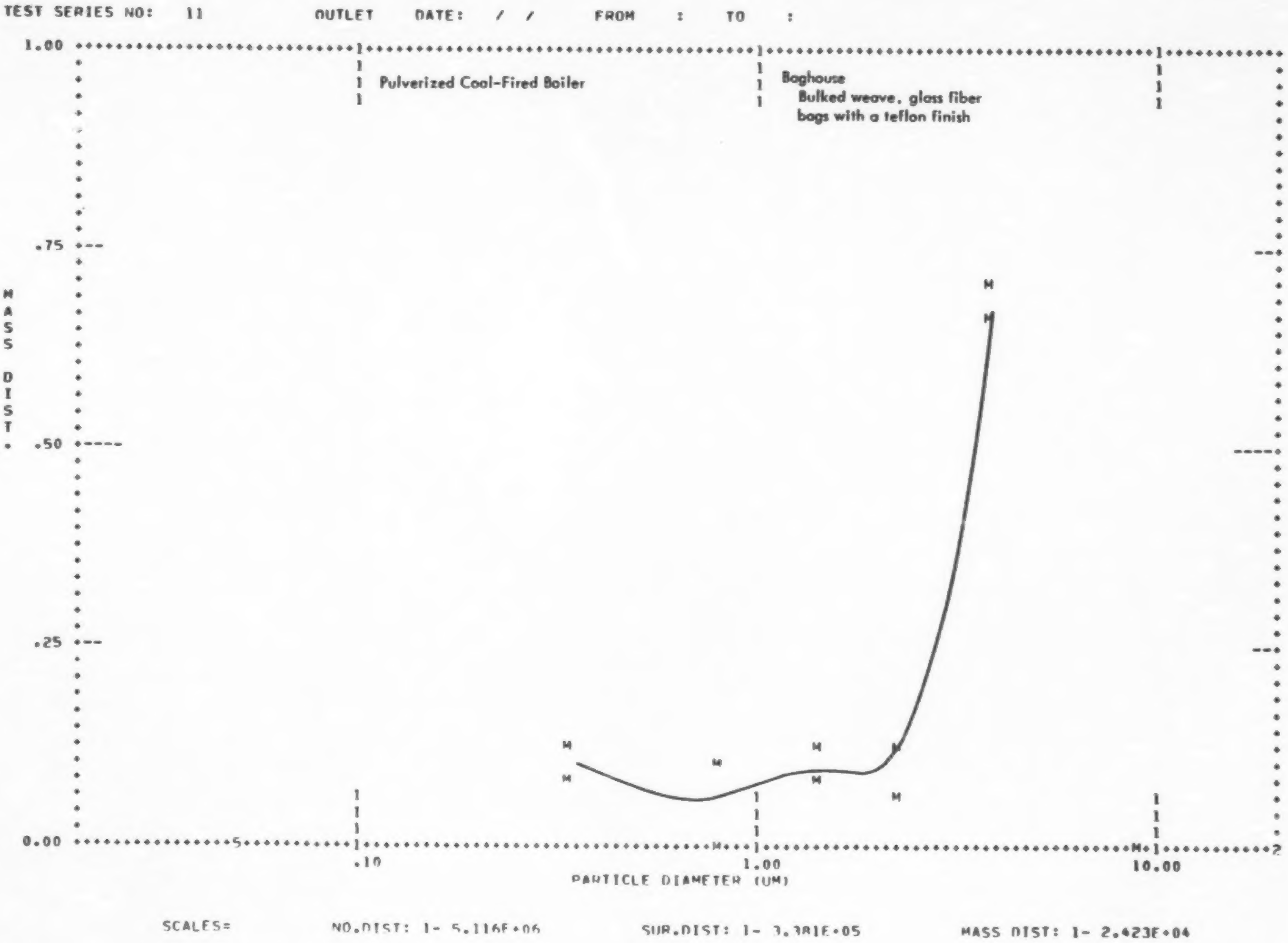


Figure A-24. Outlet Size Distributions of Test Series No. 11

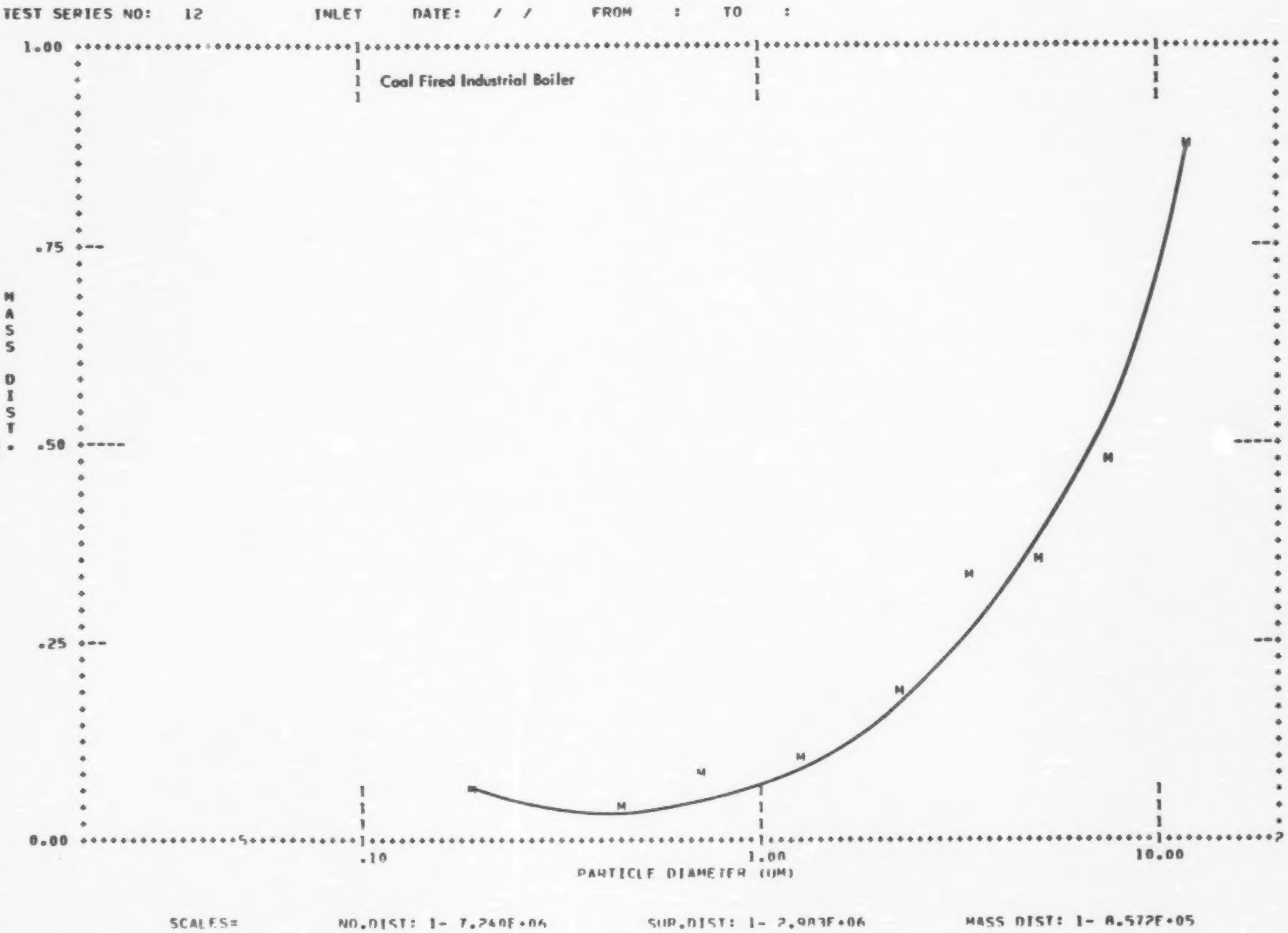


Figure A-25. Inlet Size Distributions of Test Series No. 12

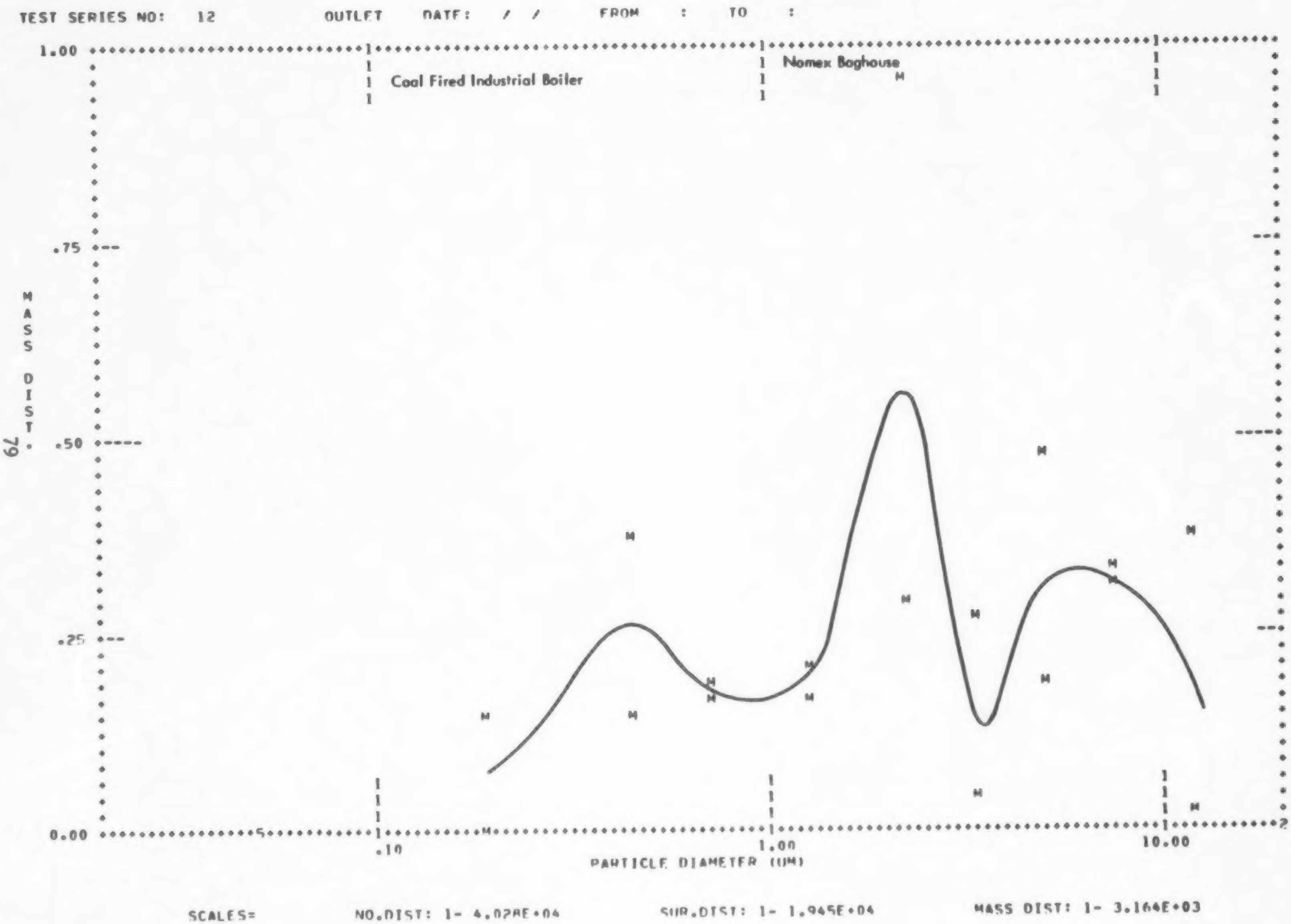


Figure A-26. Outlet Size Distributions of Test Series No. 12

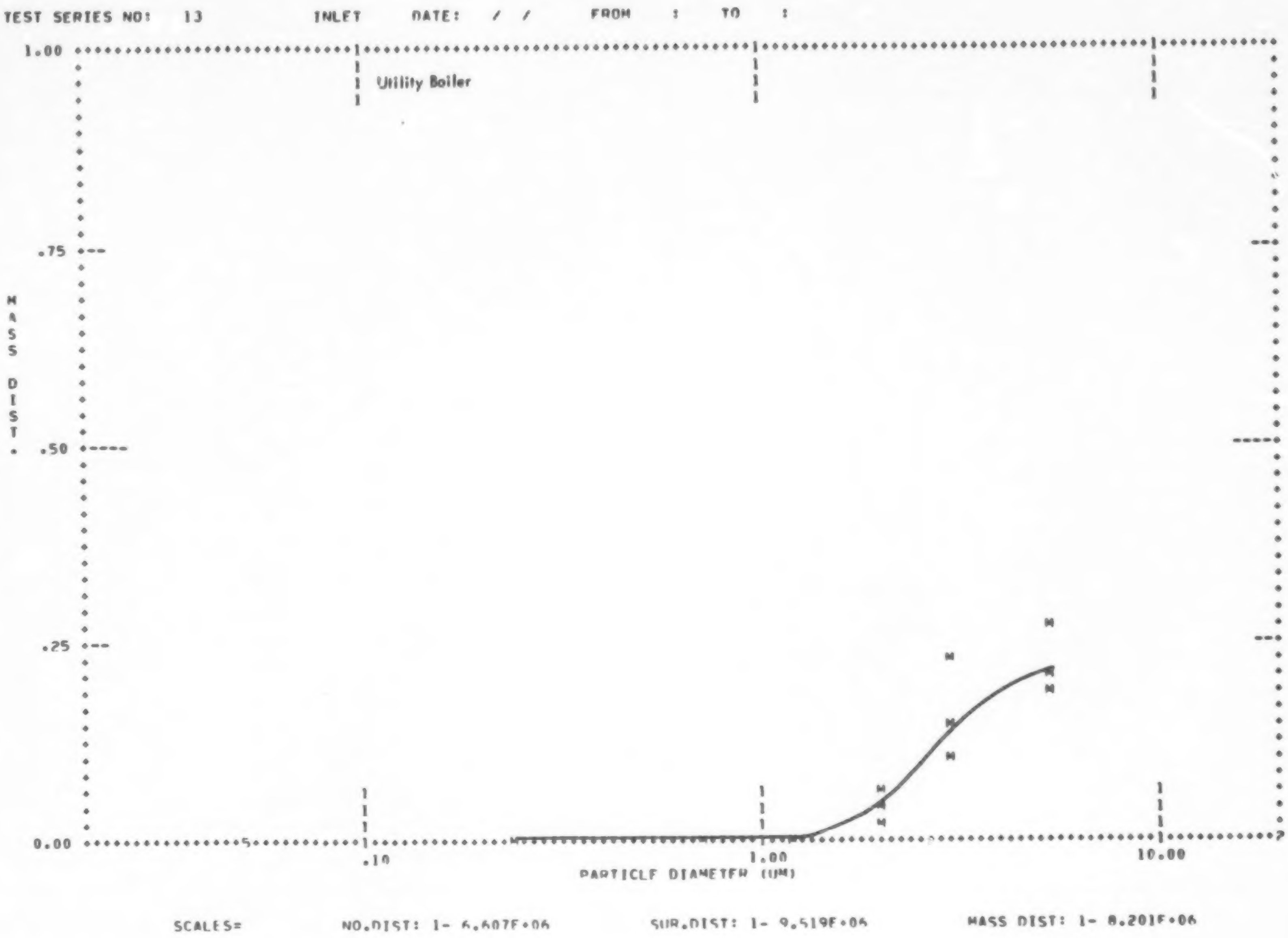


Figure A-27. Inlet Size Distributions of Test Series No. 13

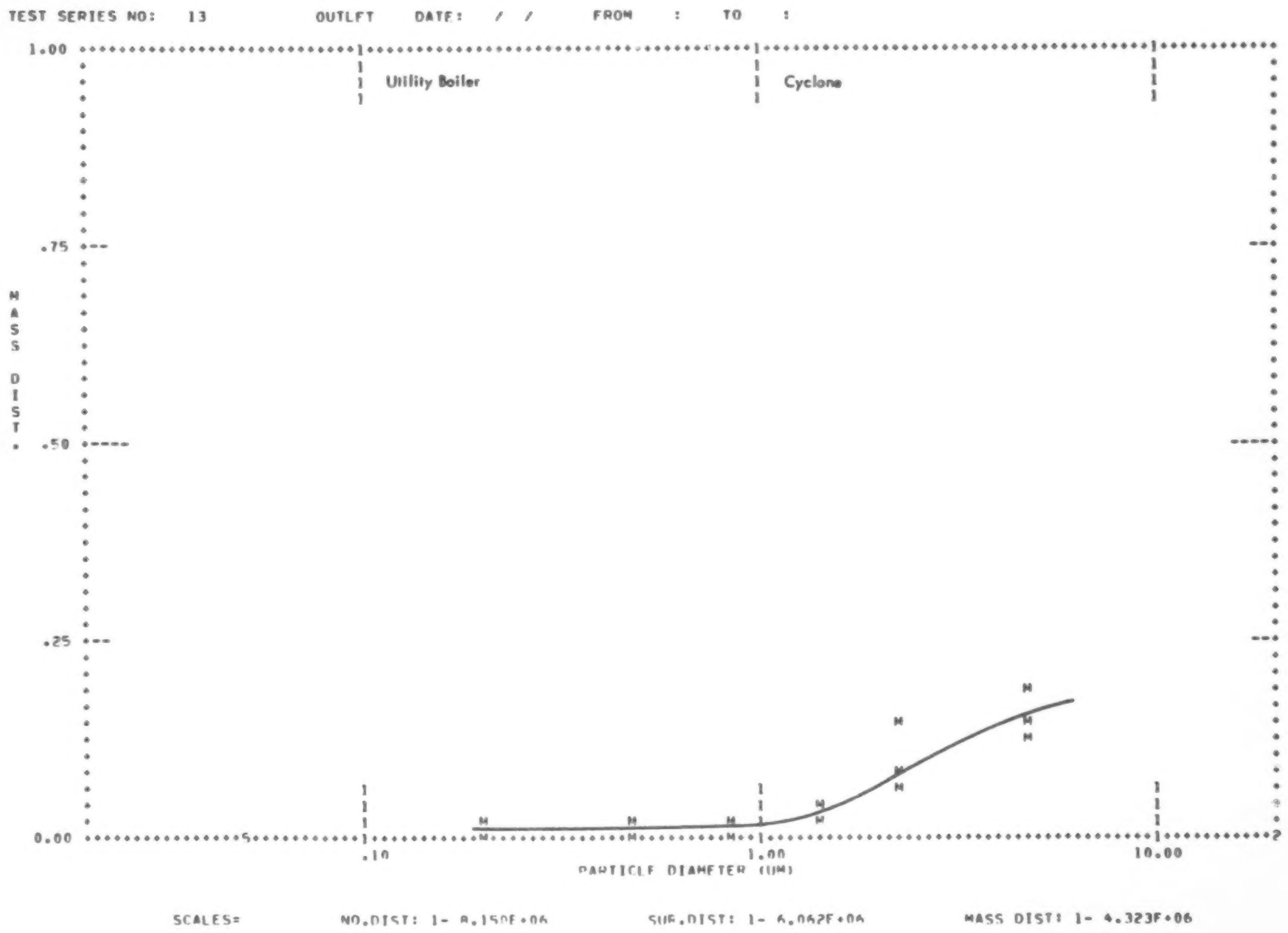


Figure A-28. Outlet Size Distributions of Test Series No. 13

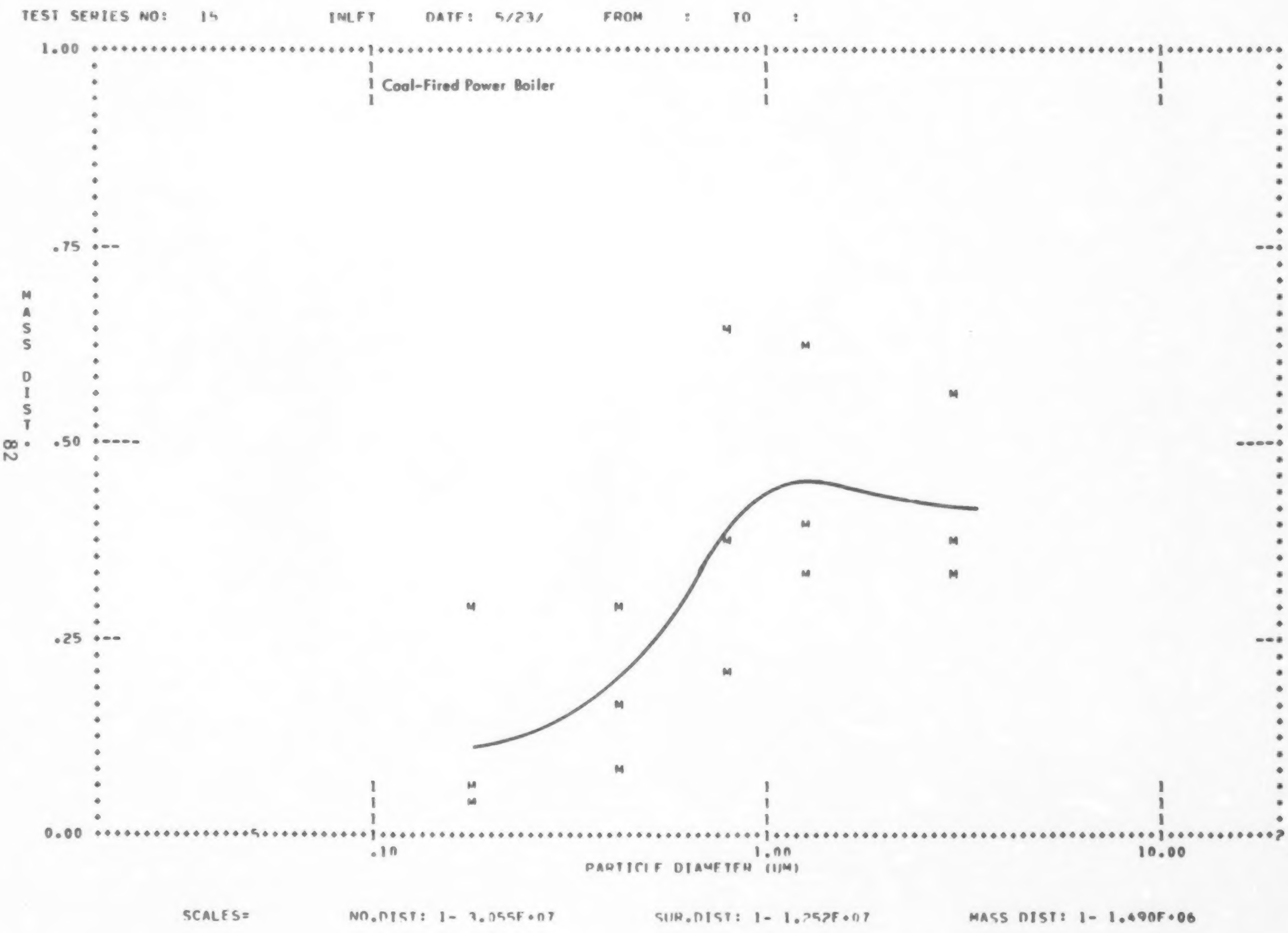


Figure A-29. Inlet Size Distributions of Test Series No. 15

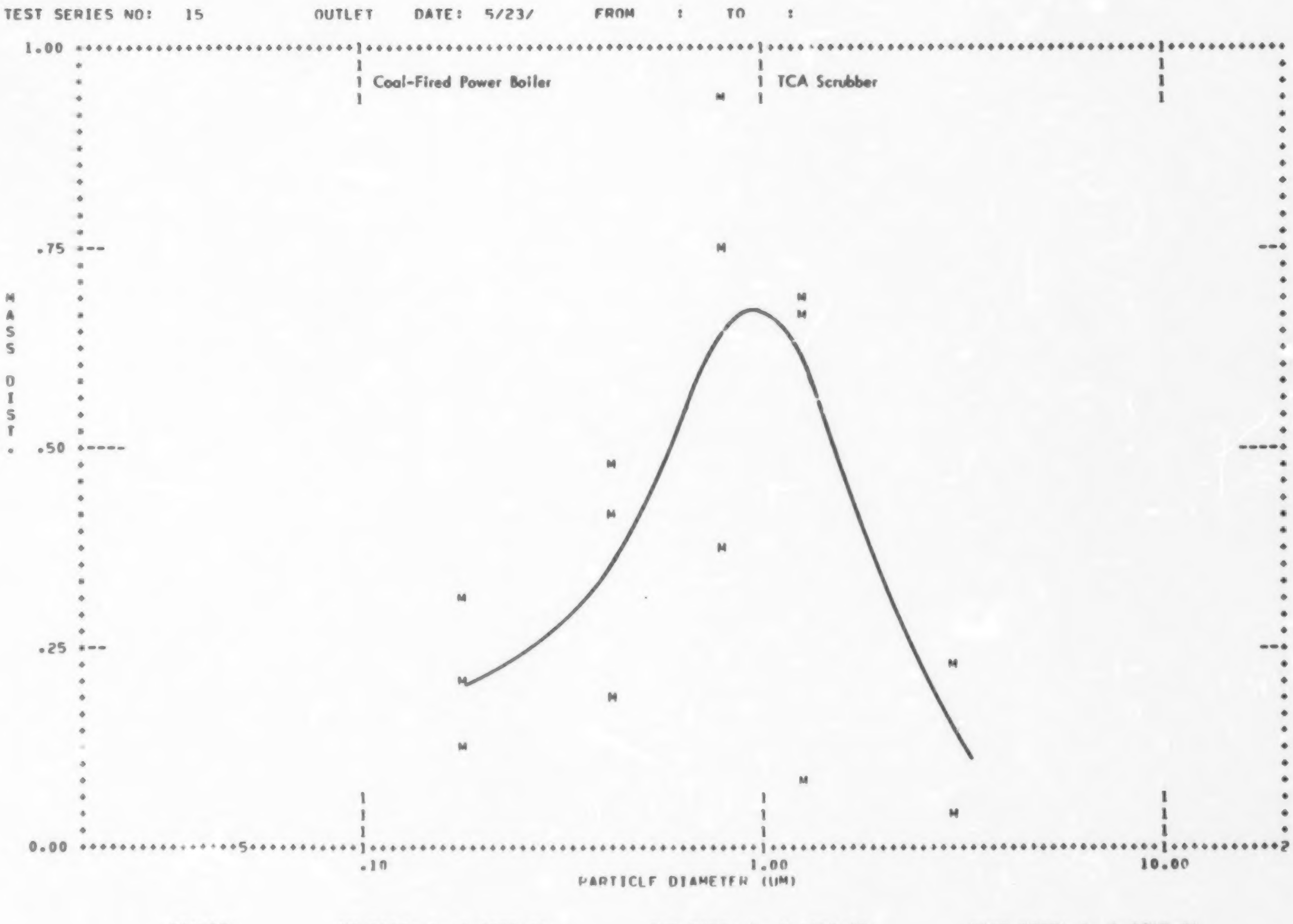


Figure A-30. Outlet Size Distributions of Test Series No. 15

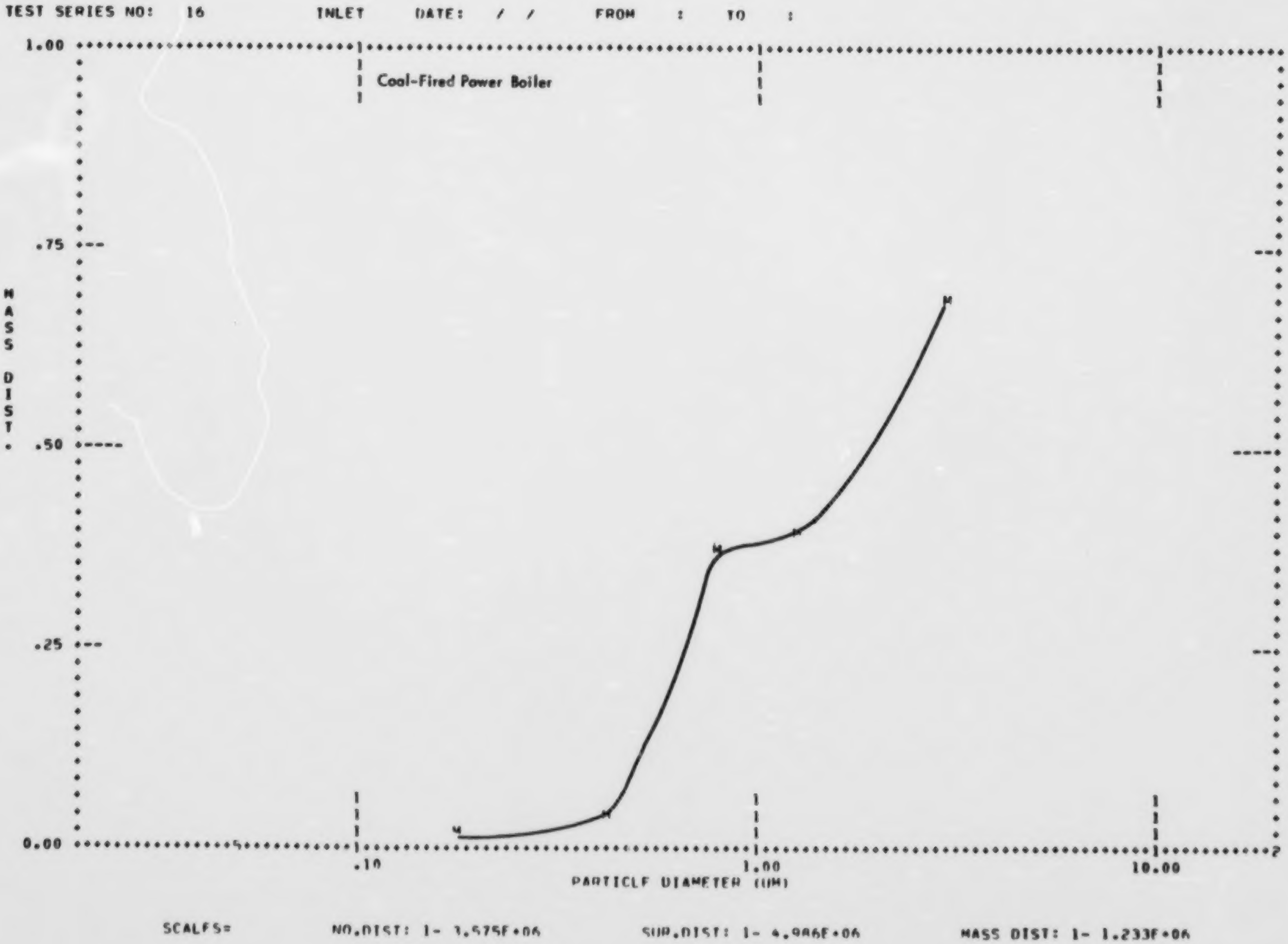


Figure A-31. Inlet Size Distributions of Test Series No. 16

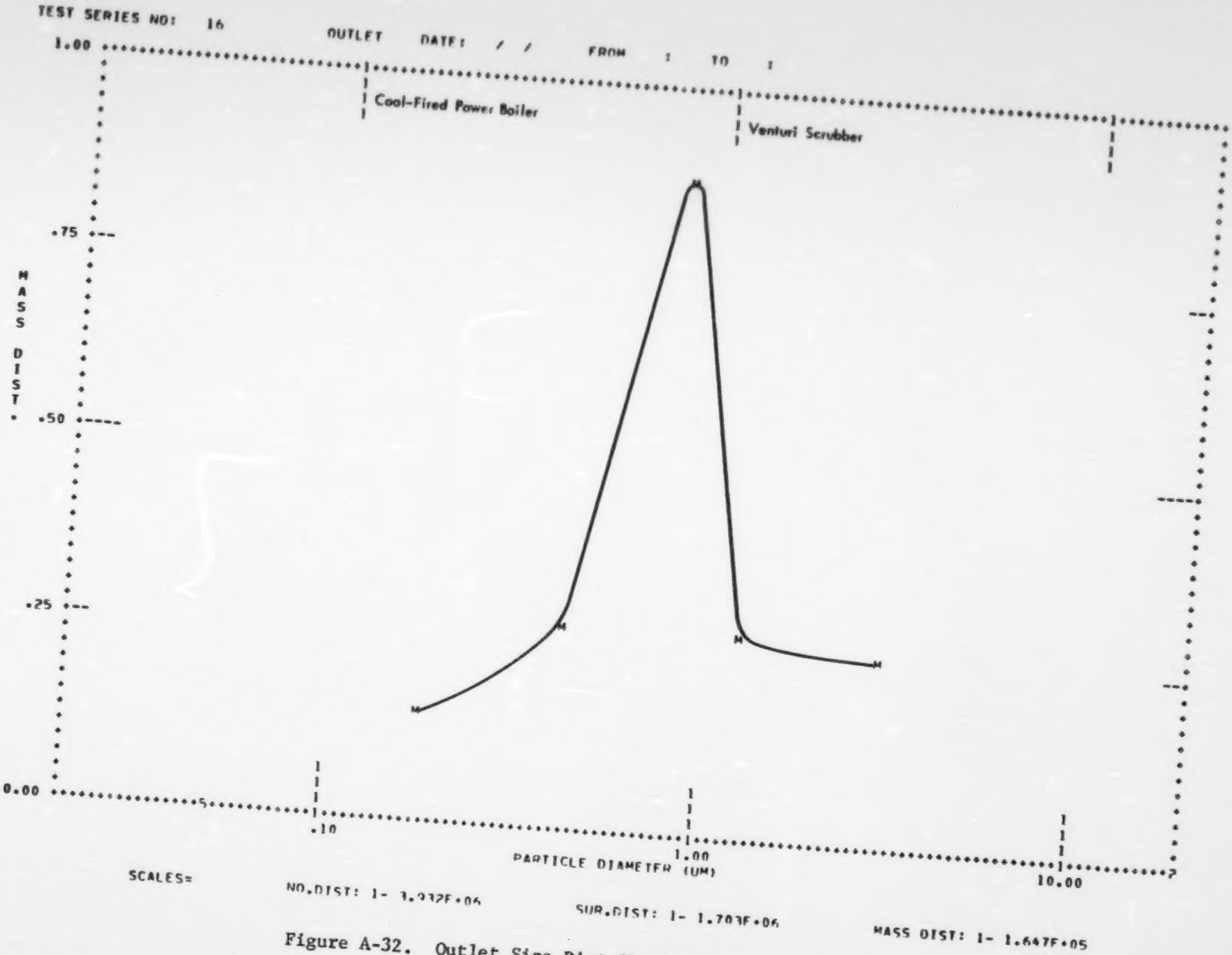


Figure A-32. Outlet Size Distributions of Test Series No. 16

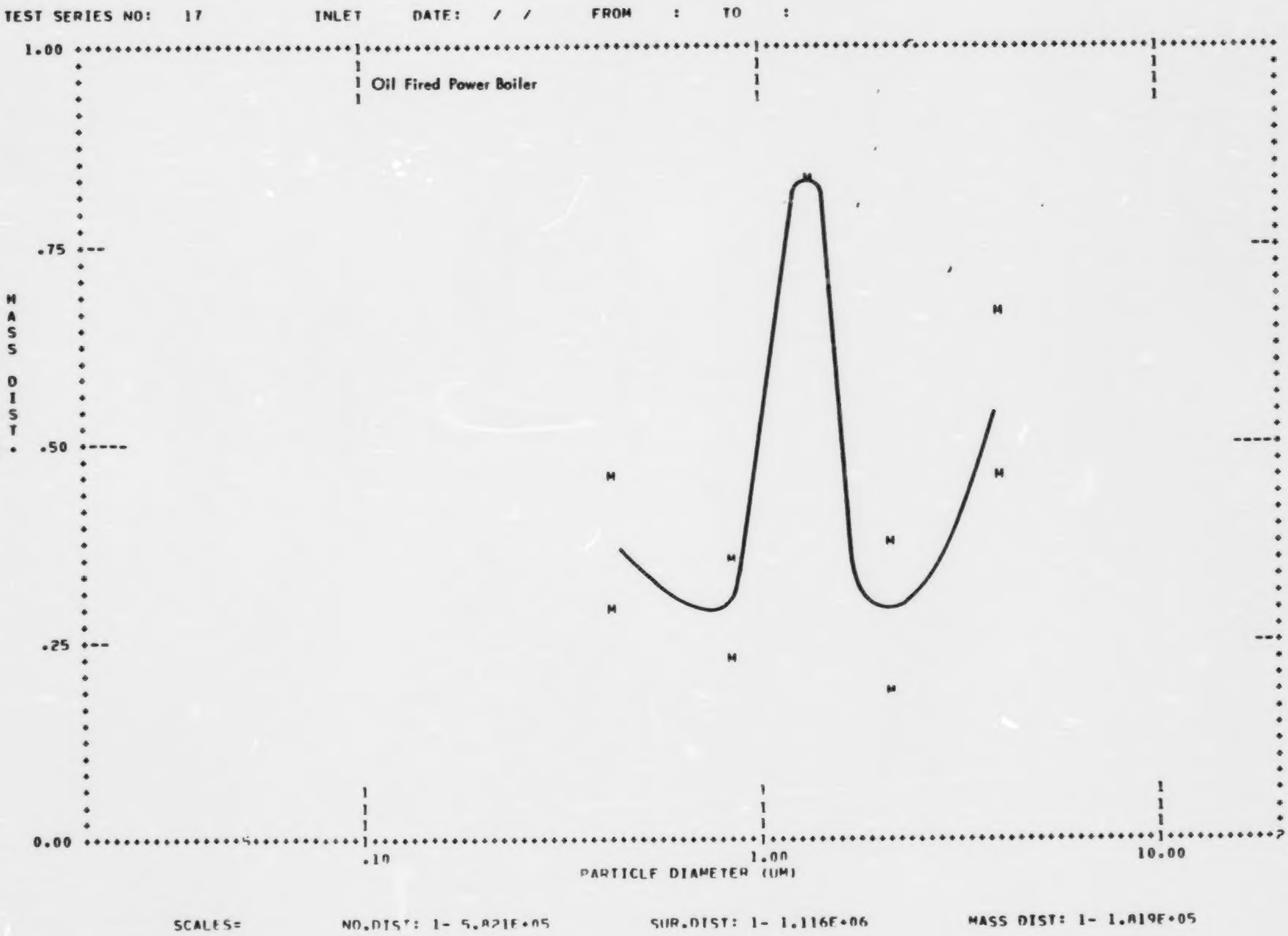
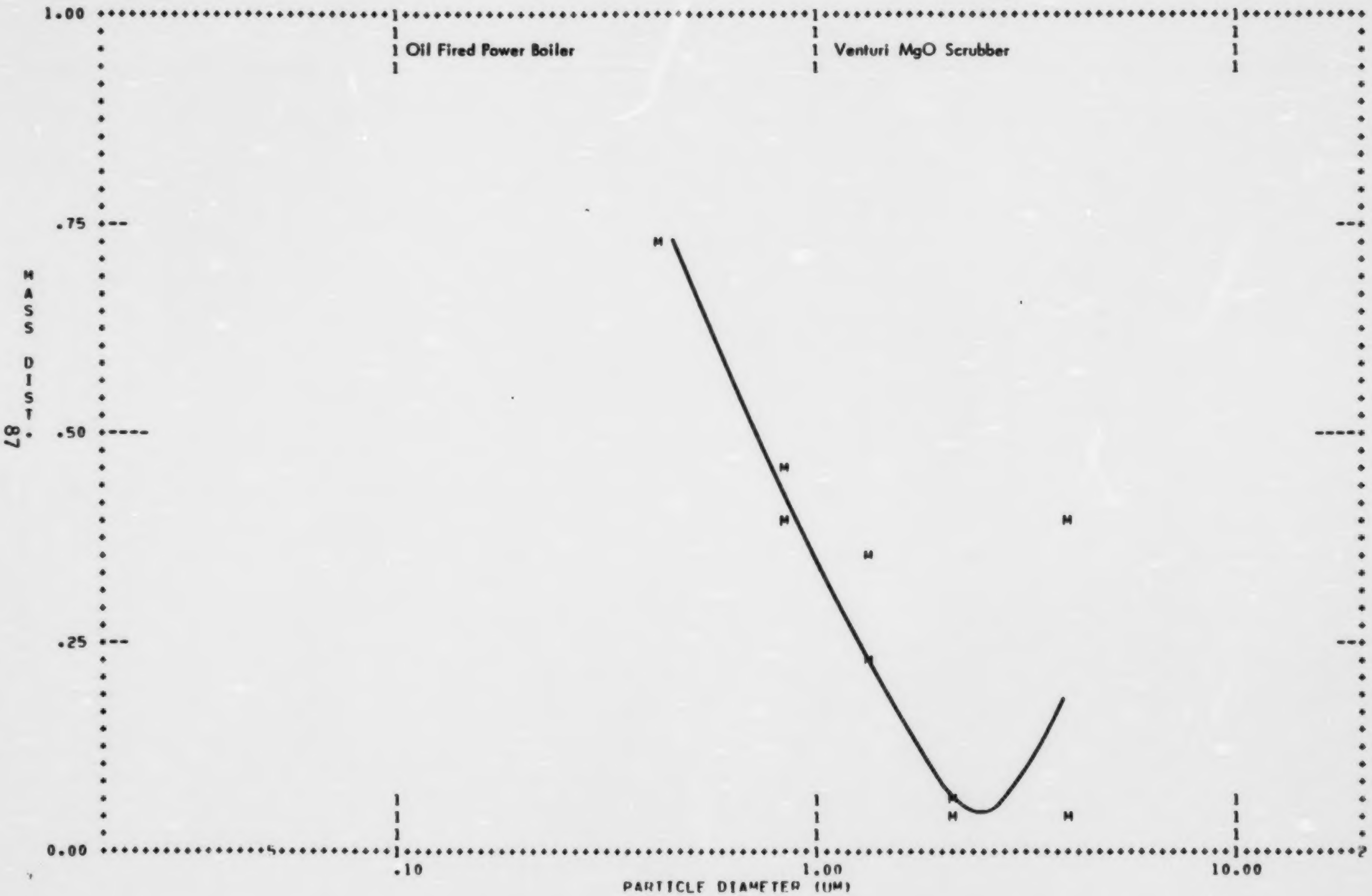


Figure A-33. Inlet Size Distributions of Test Series No. 17

TEST SERIES NO: 17 OUTLET DATE: / / FROM : TO :



SCALES= NO.DIST: 1- 1.699E+06 SUR.DIST: 1- 2.337E+06 MASS DIST: 1- 2.281E+05

Figure A-34. Outlet Size Distributions of Test Series No. 17

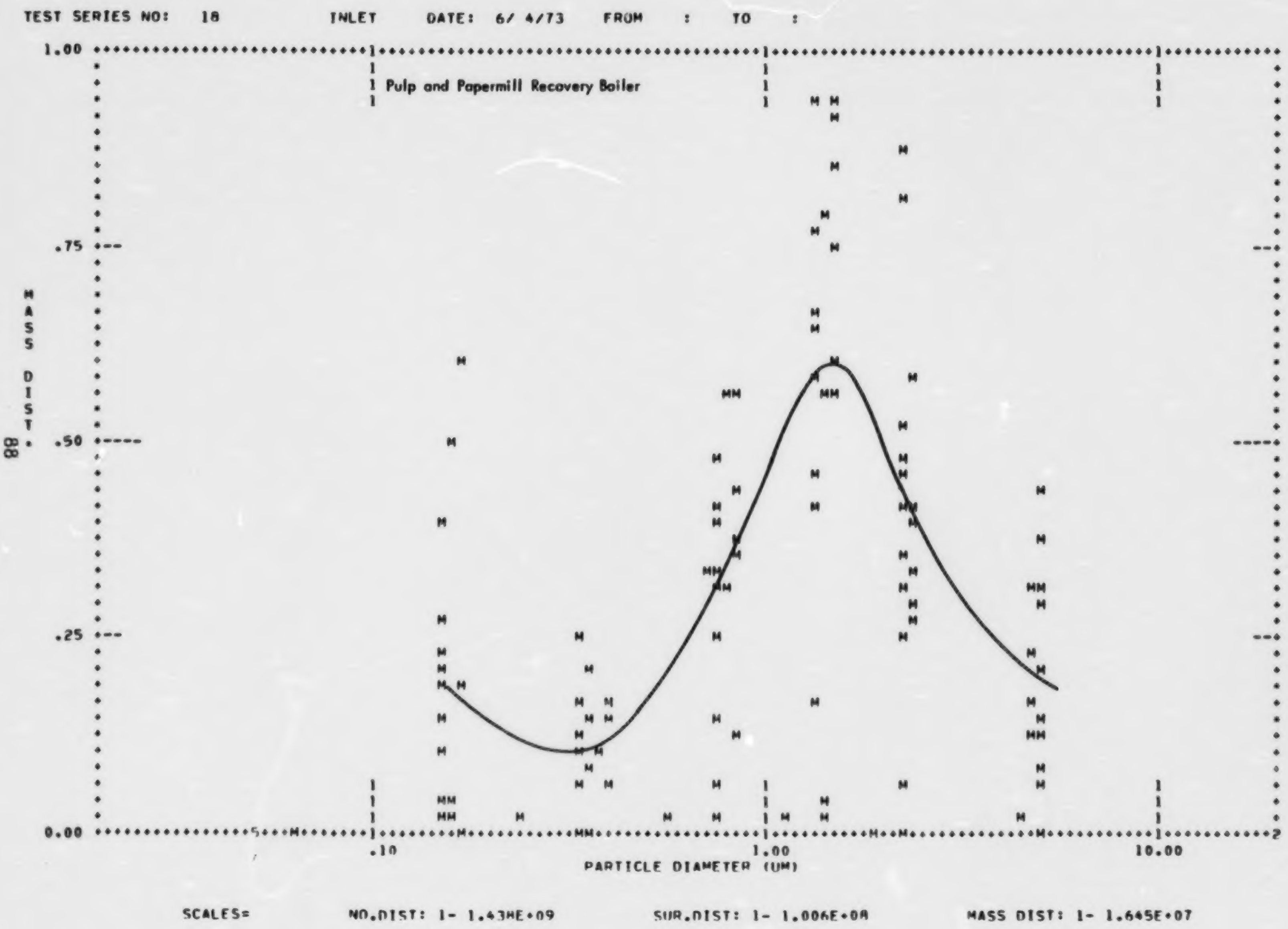


Figure A-35. Inlet Size Distributions of Test Series No. 18

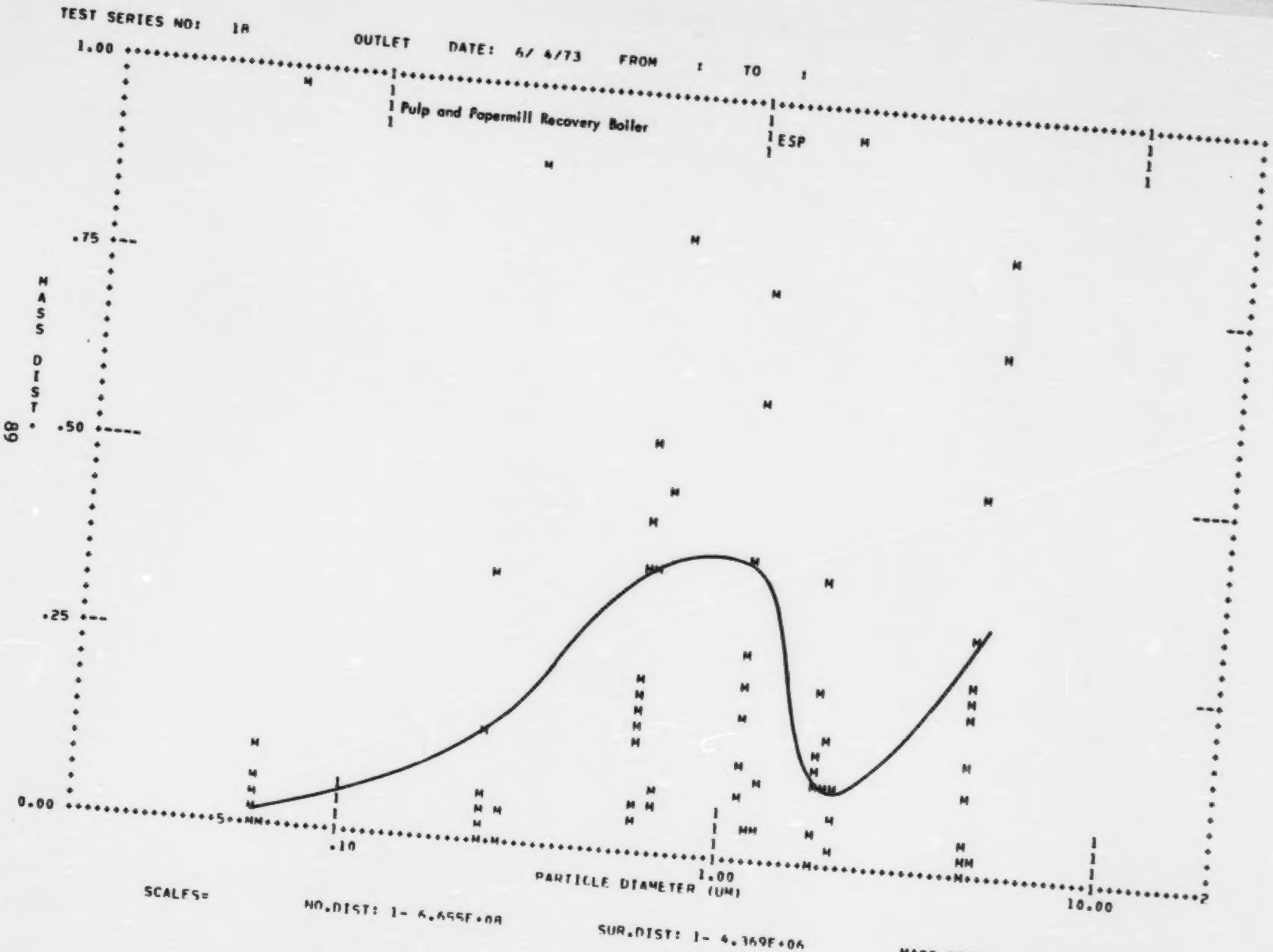


Figure A-36. Outlet Size Distributions of Test Series No. 18

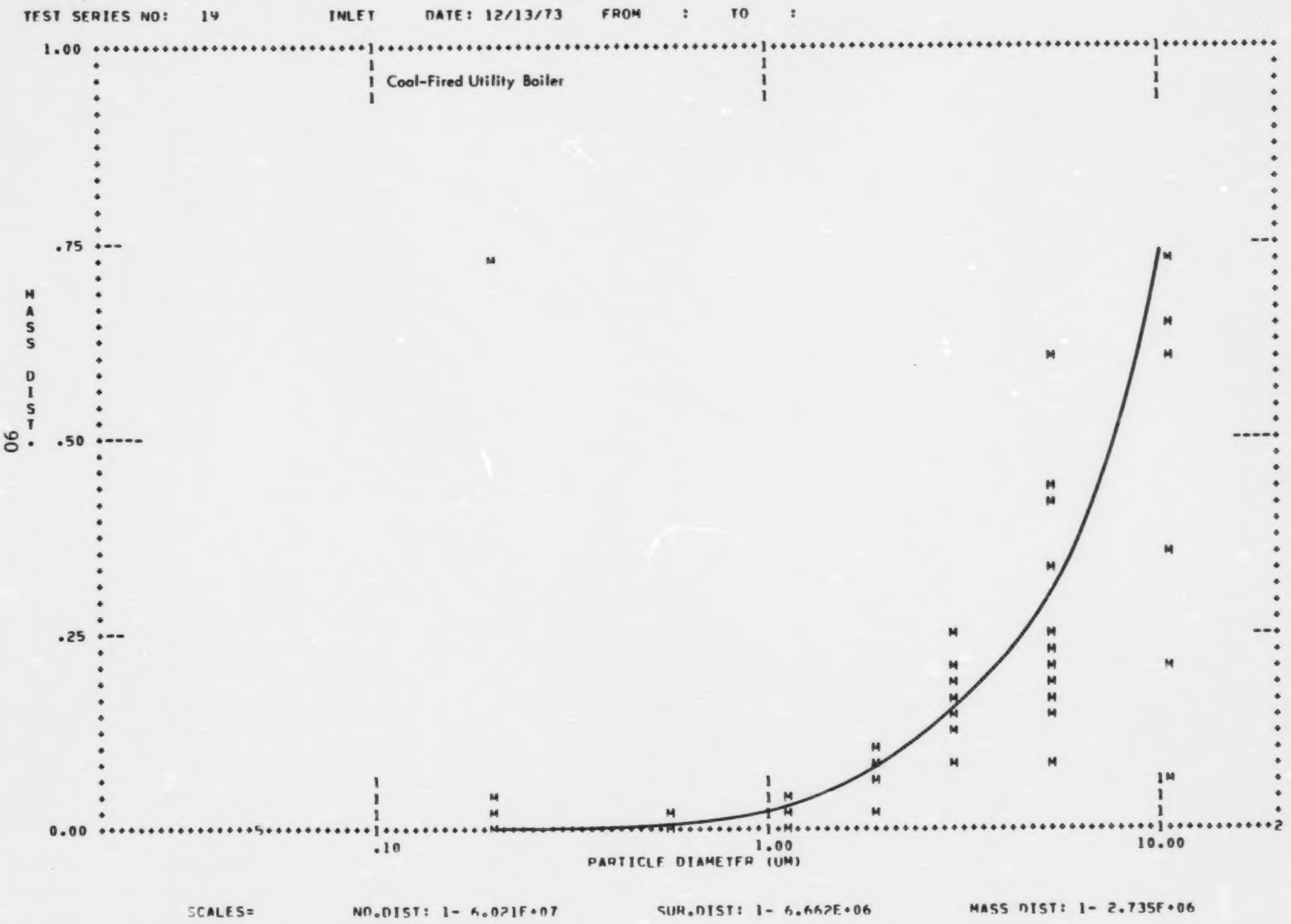


Figure A-37. Inlet Size Distributions of Test Series No. 19

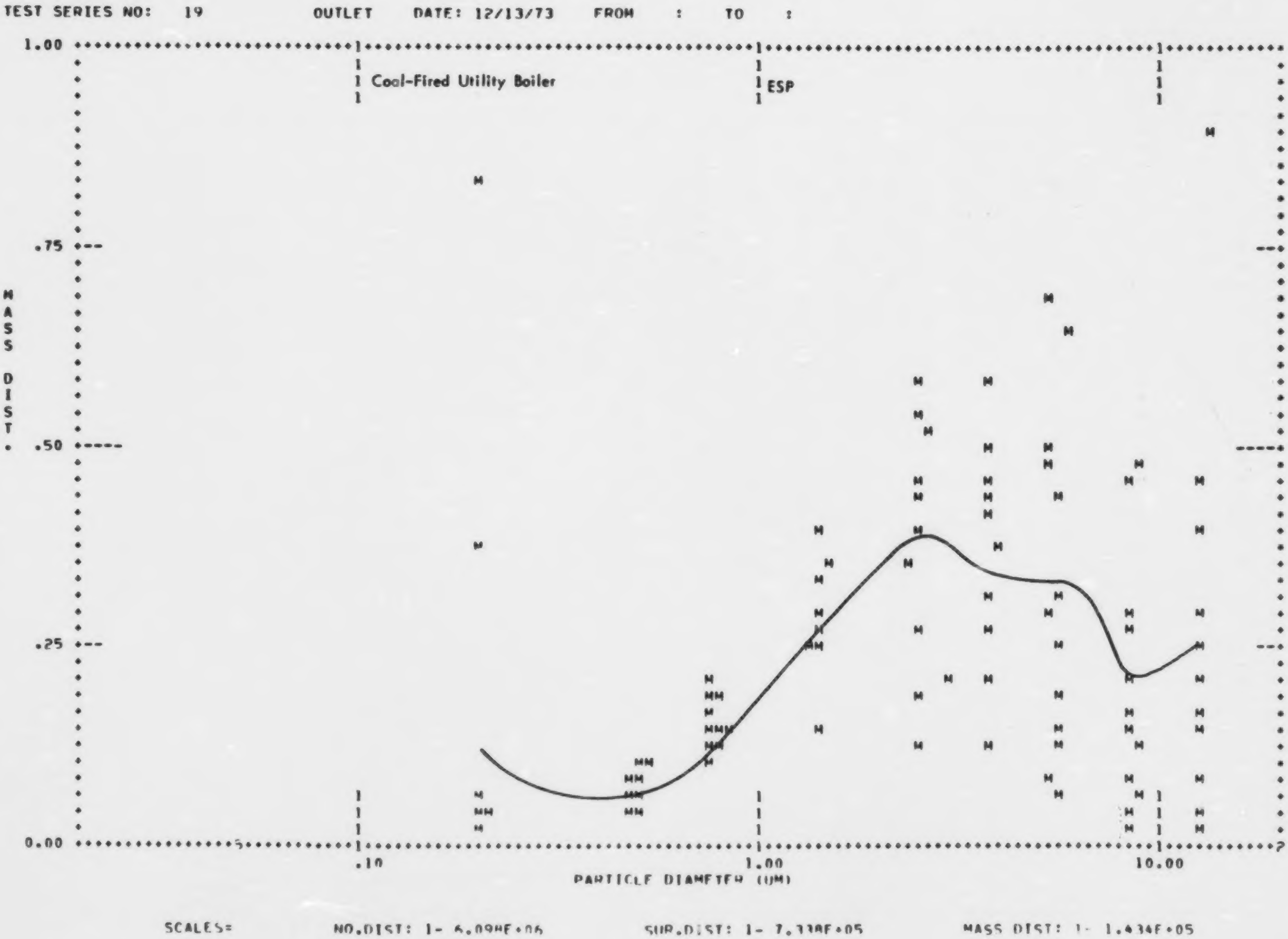


Figure A-38. Outlet Size Distributions of Test Series No. 19

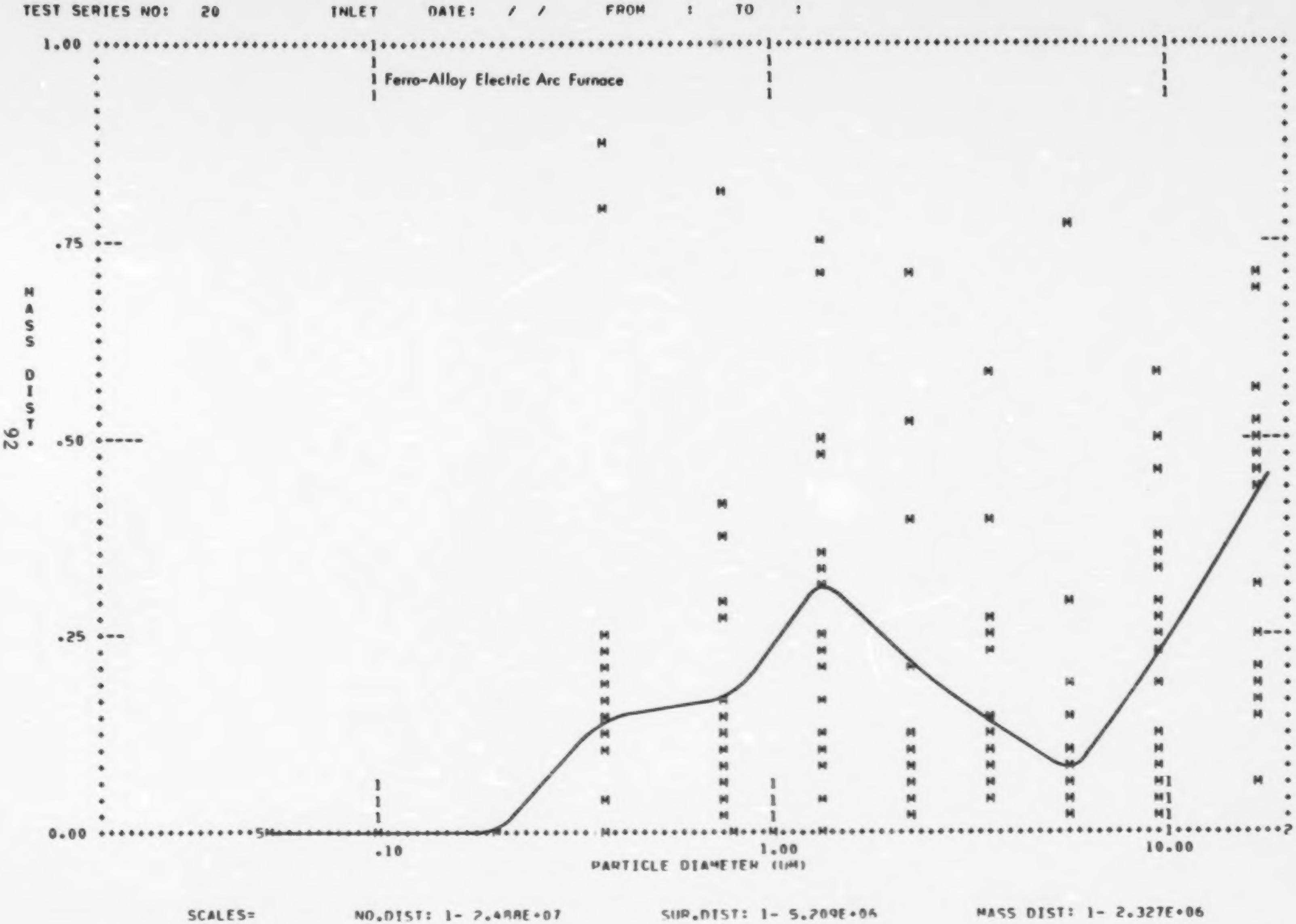


Figure A-39. Inlet Size Distributions of Test Series No. 20

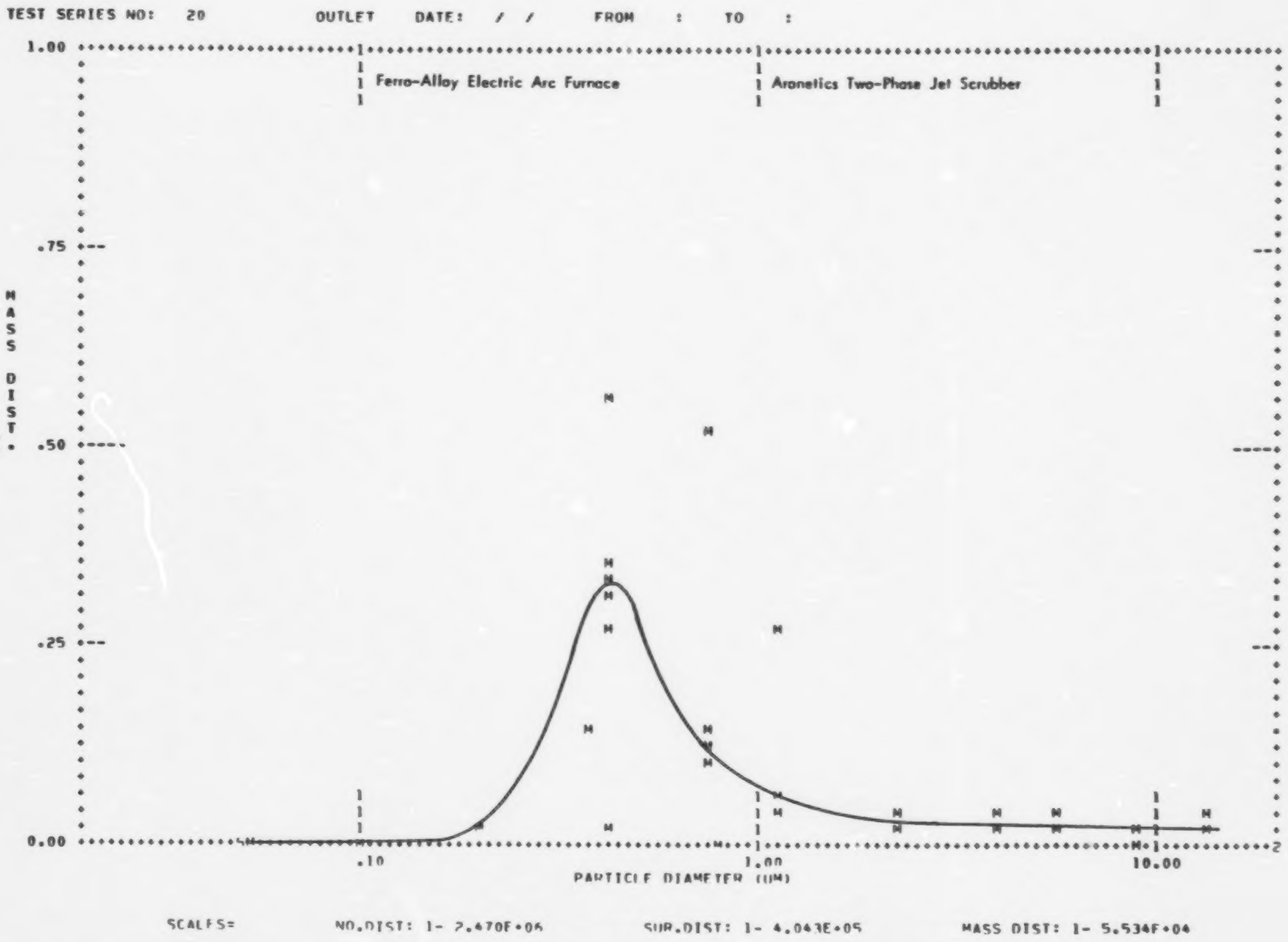


Figure A-40. Outlet Size Distributions of Test Series No. 20

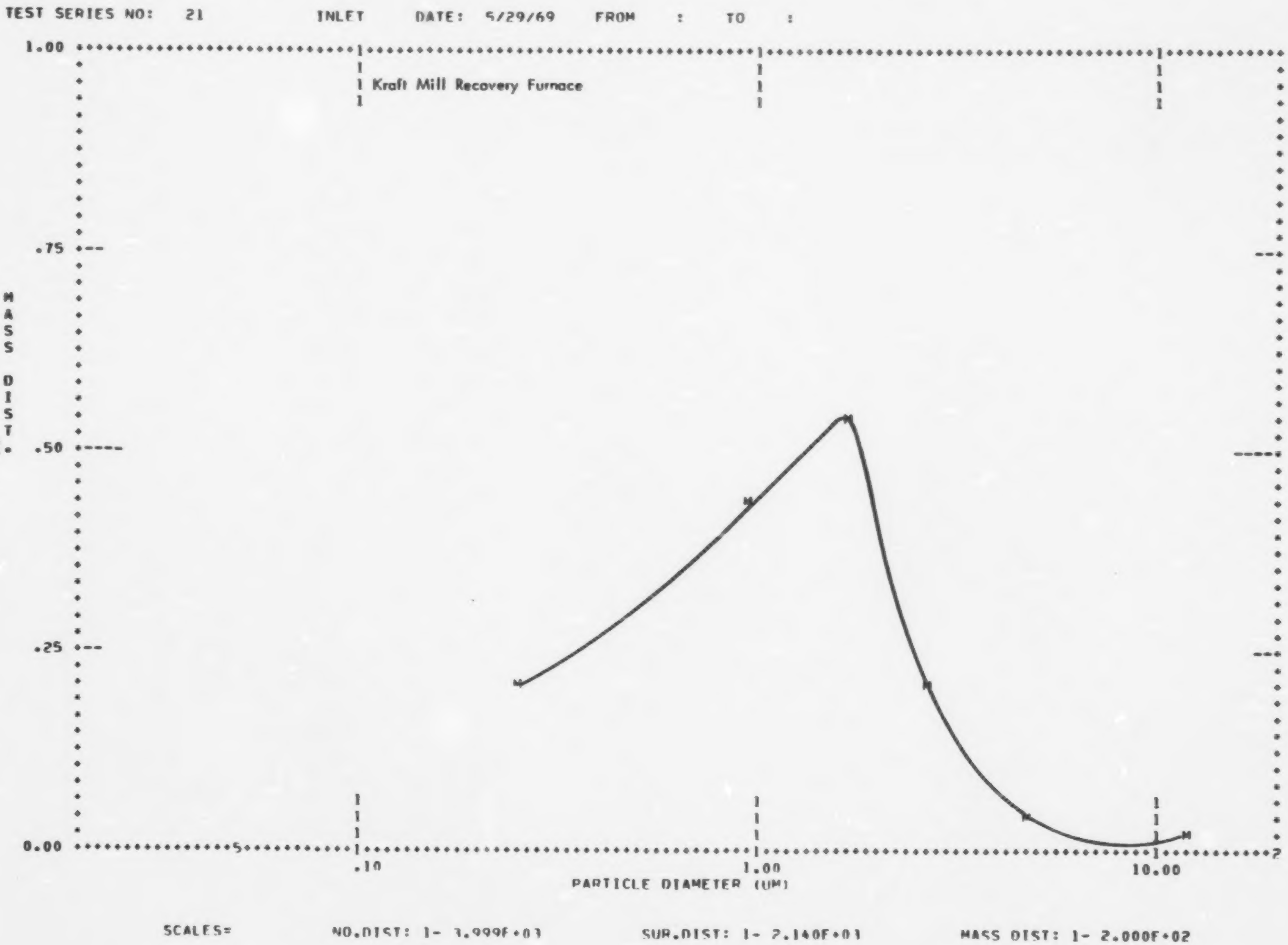


Figure A-41. Inlet Size Distributions of Test Series No. 21

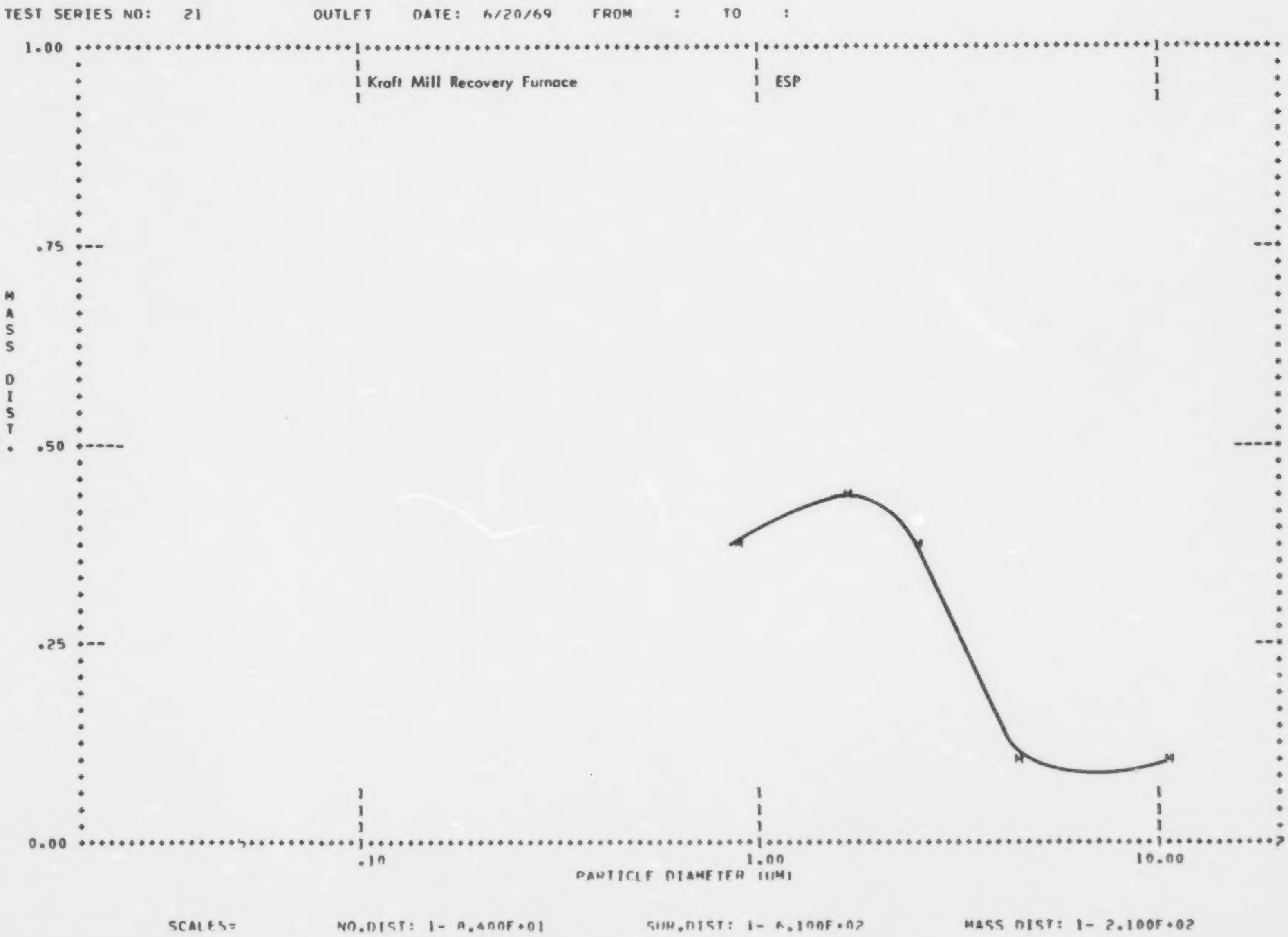


Figure A-42. Outlet Size Distributions of Test Series No. 21

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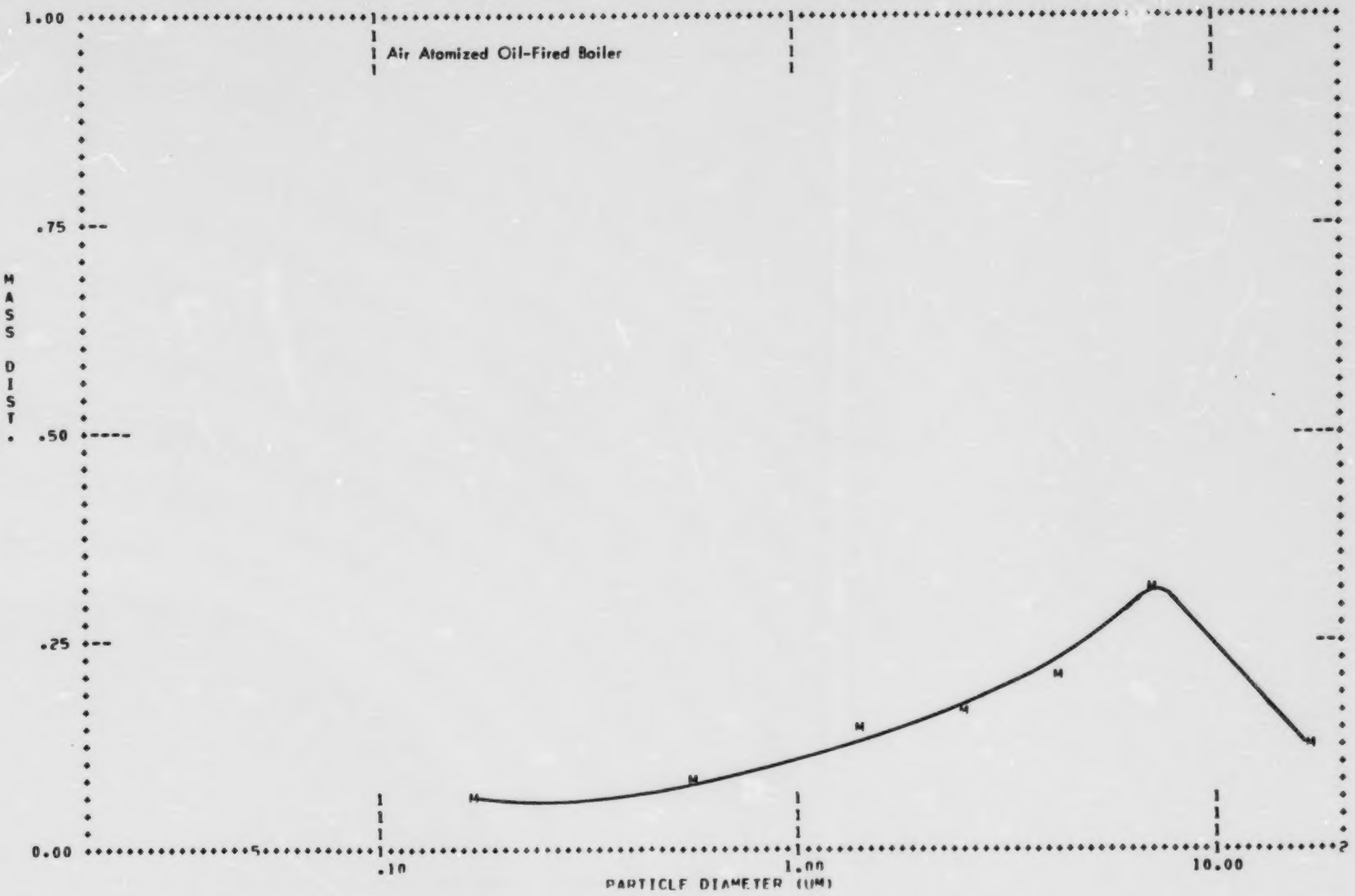

SCALES= NO.DIST: 1- 6.420E+06 SUR.DIST: 1- 1.629E+06 MASS DIST: 1- 4.180E+05

Figure A-43. Inlet Size Distributions of Test Series No. 22

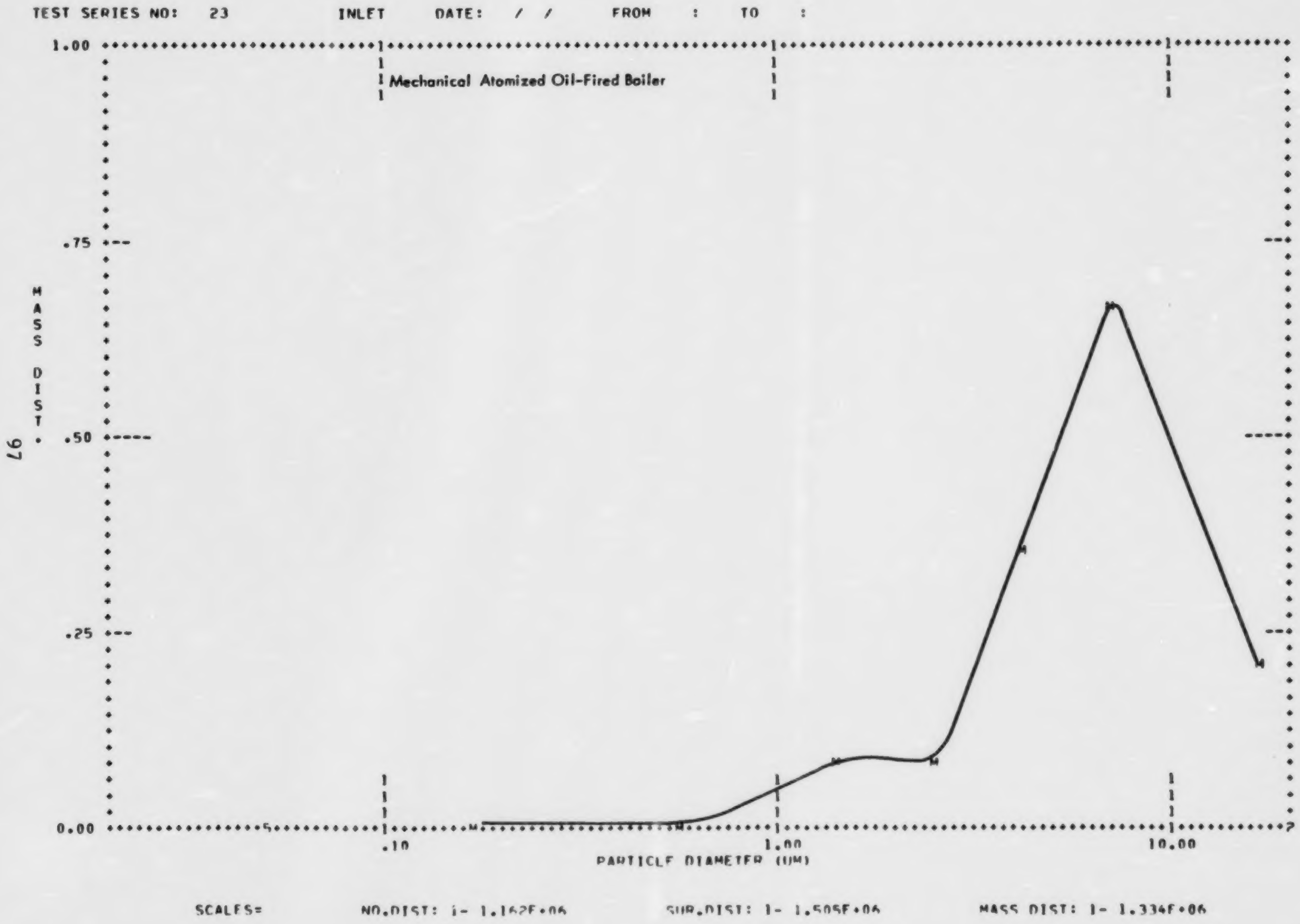

Figure A-44. Inlet Size Distributions of Test Series No. 23

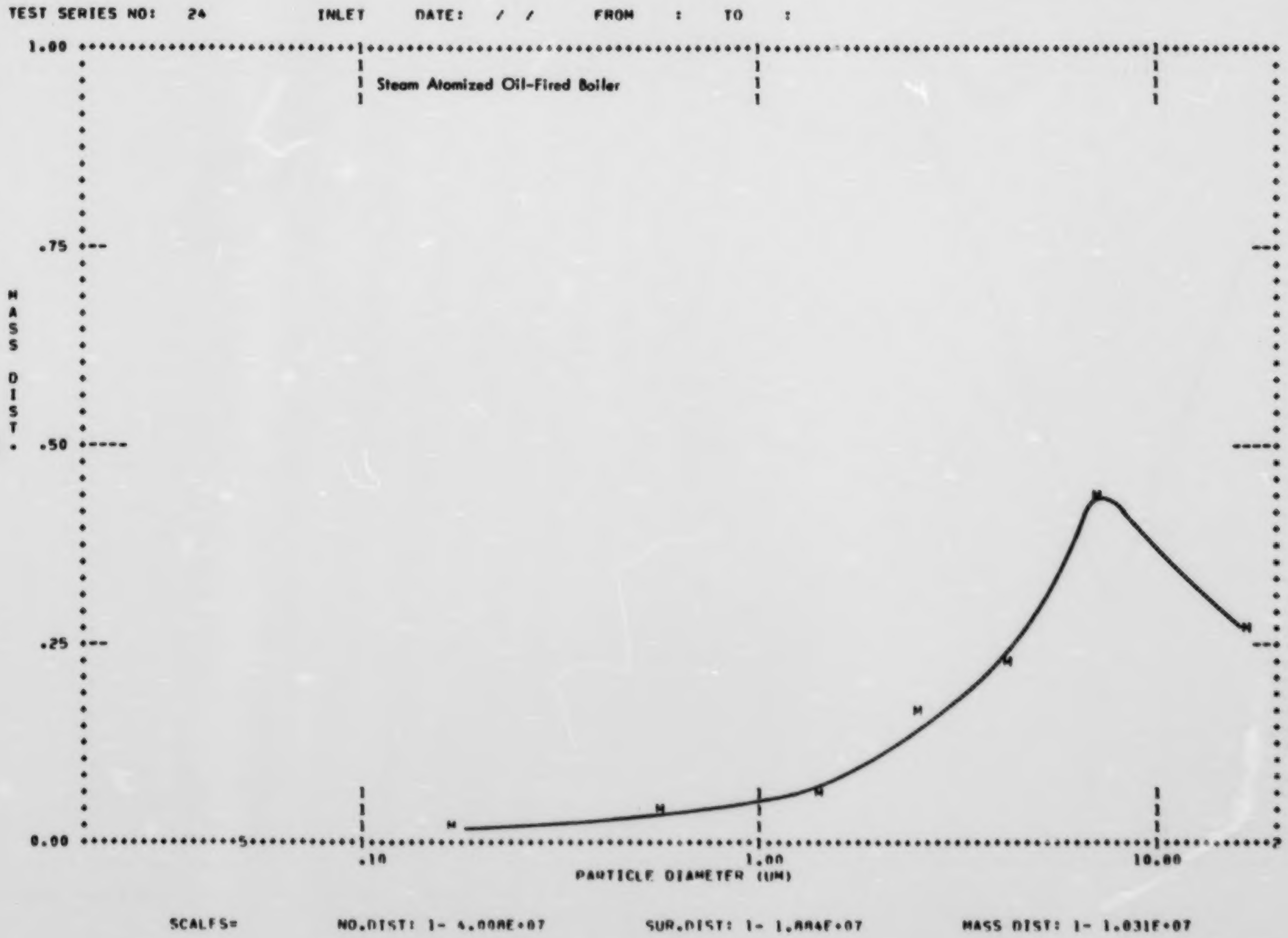

Figure A-45. Inlet Size Distributions of Test Series No. 24

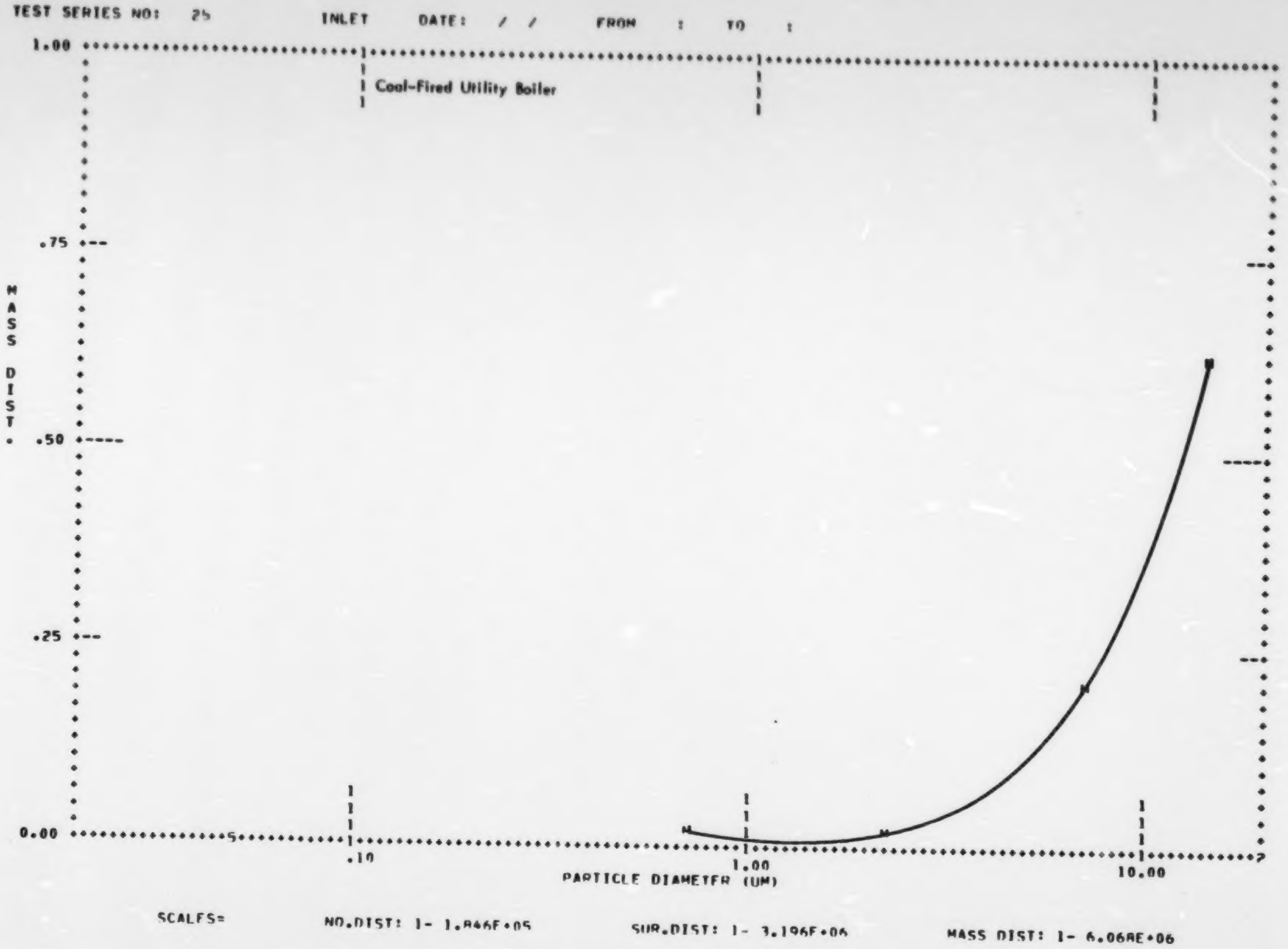

Figure A-46. Inlet Size Distributions of Test Series No. 25

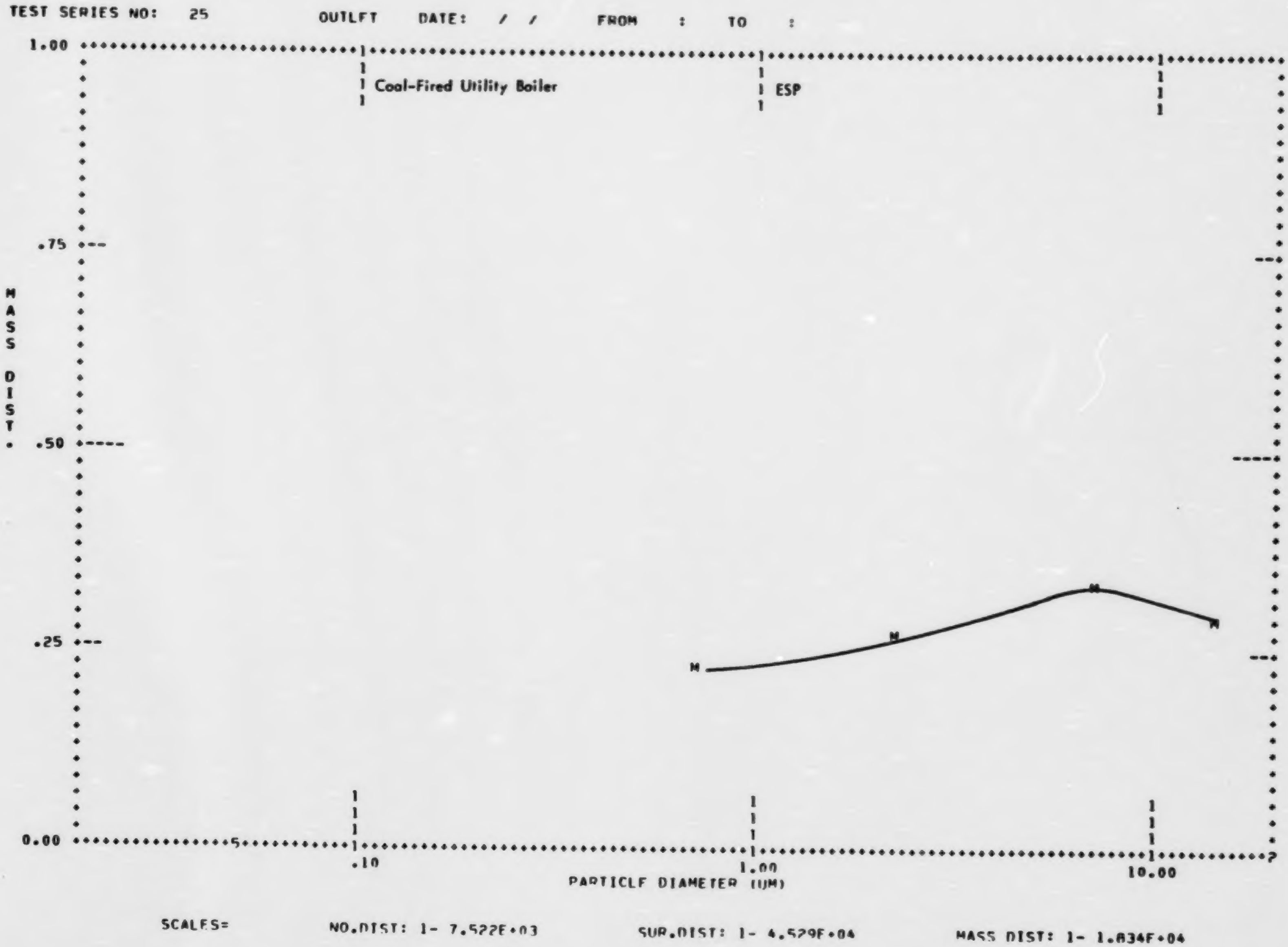

Figure A-47. Outlet Size Distributions of Test Series No. 25

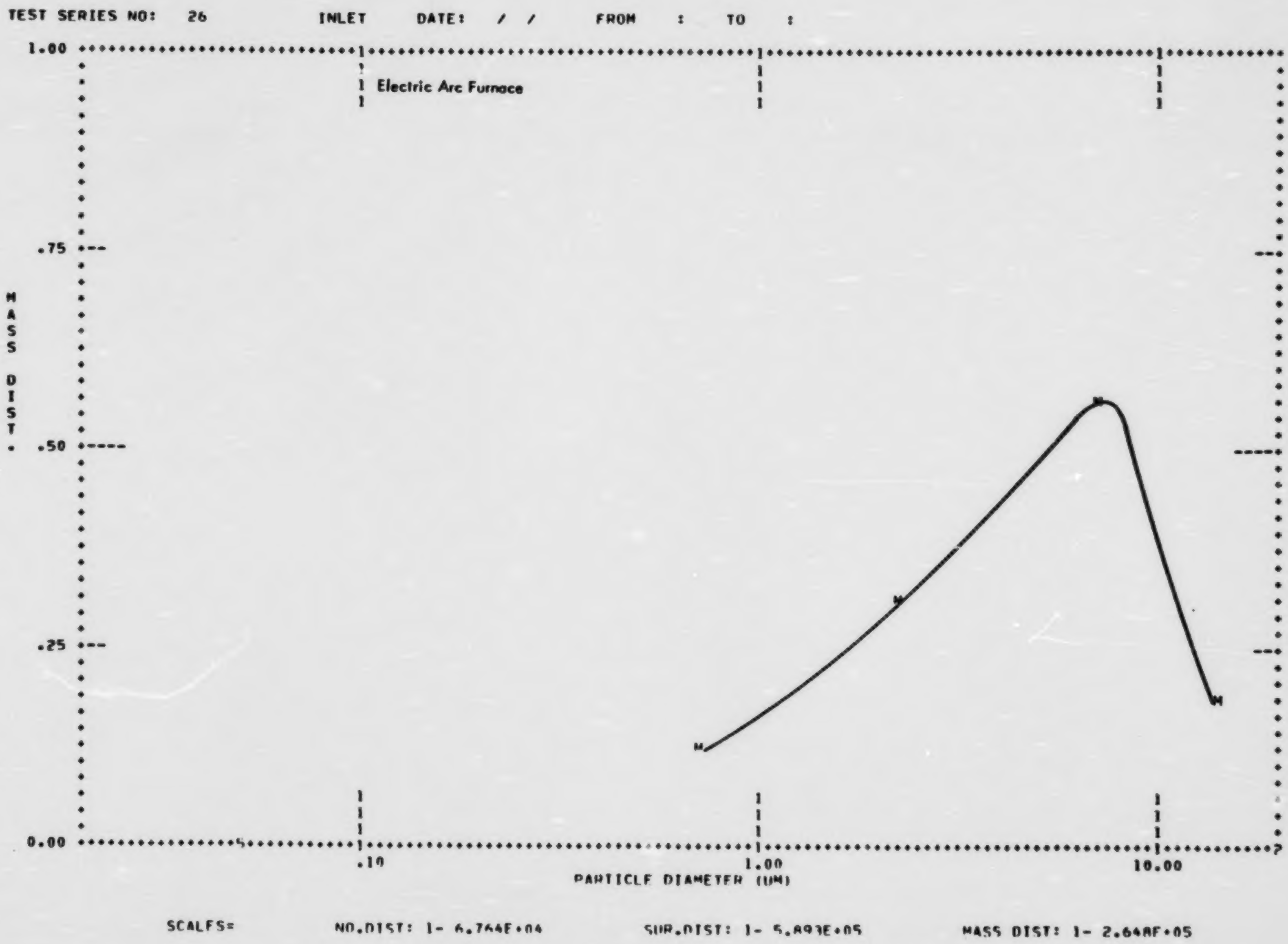

Figure A-48. Inlet Size Distributions of Test Series No. 26

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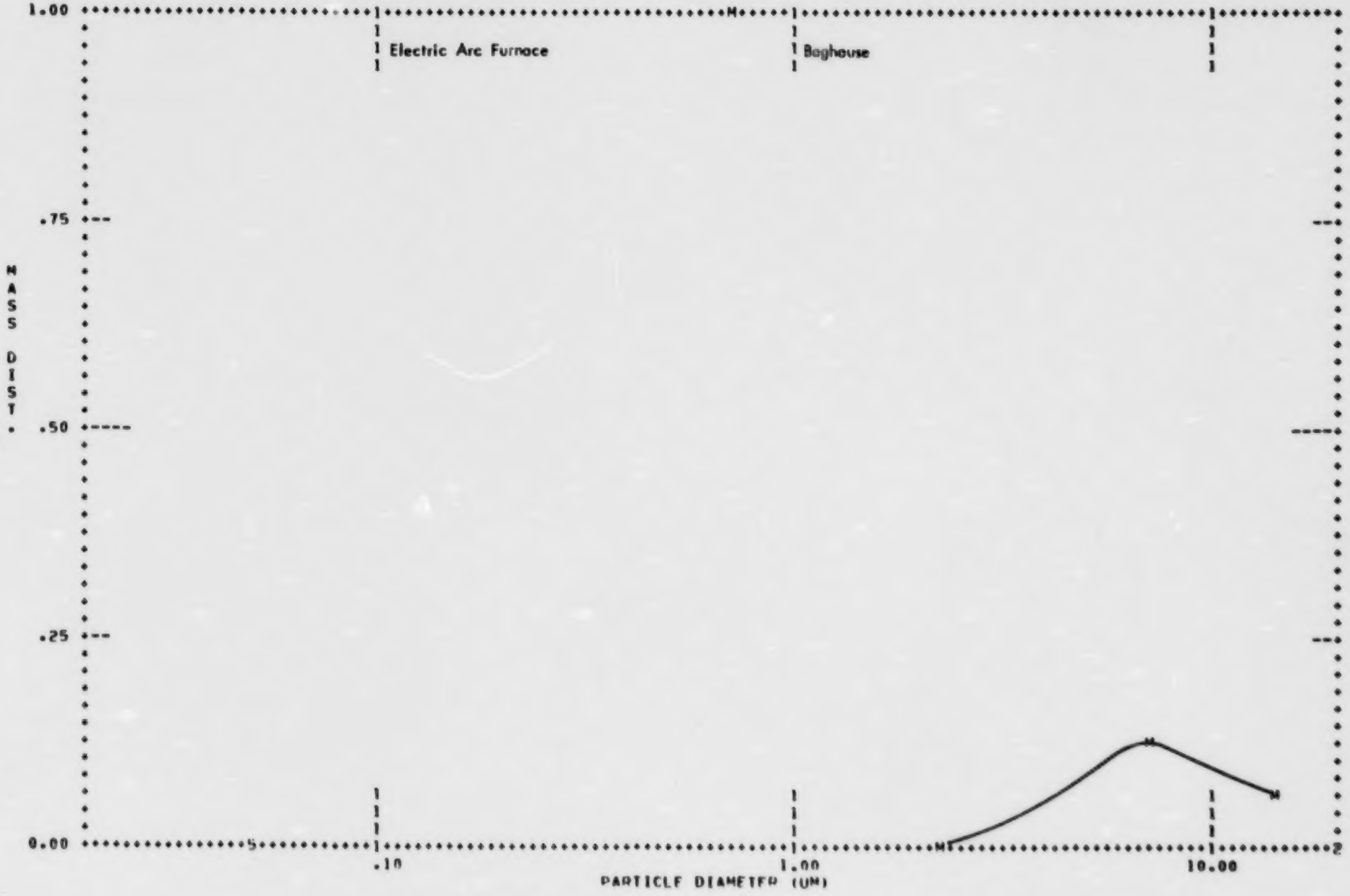

SCALES= NO.DIST: 1- 2.600E+01 SUR.DIST: 1- 8.400E+01 MASS DIST: 1- 1.600E+01

Figure A-49. Outlet Size Distributions of Test Series No. 26

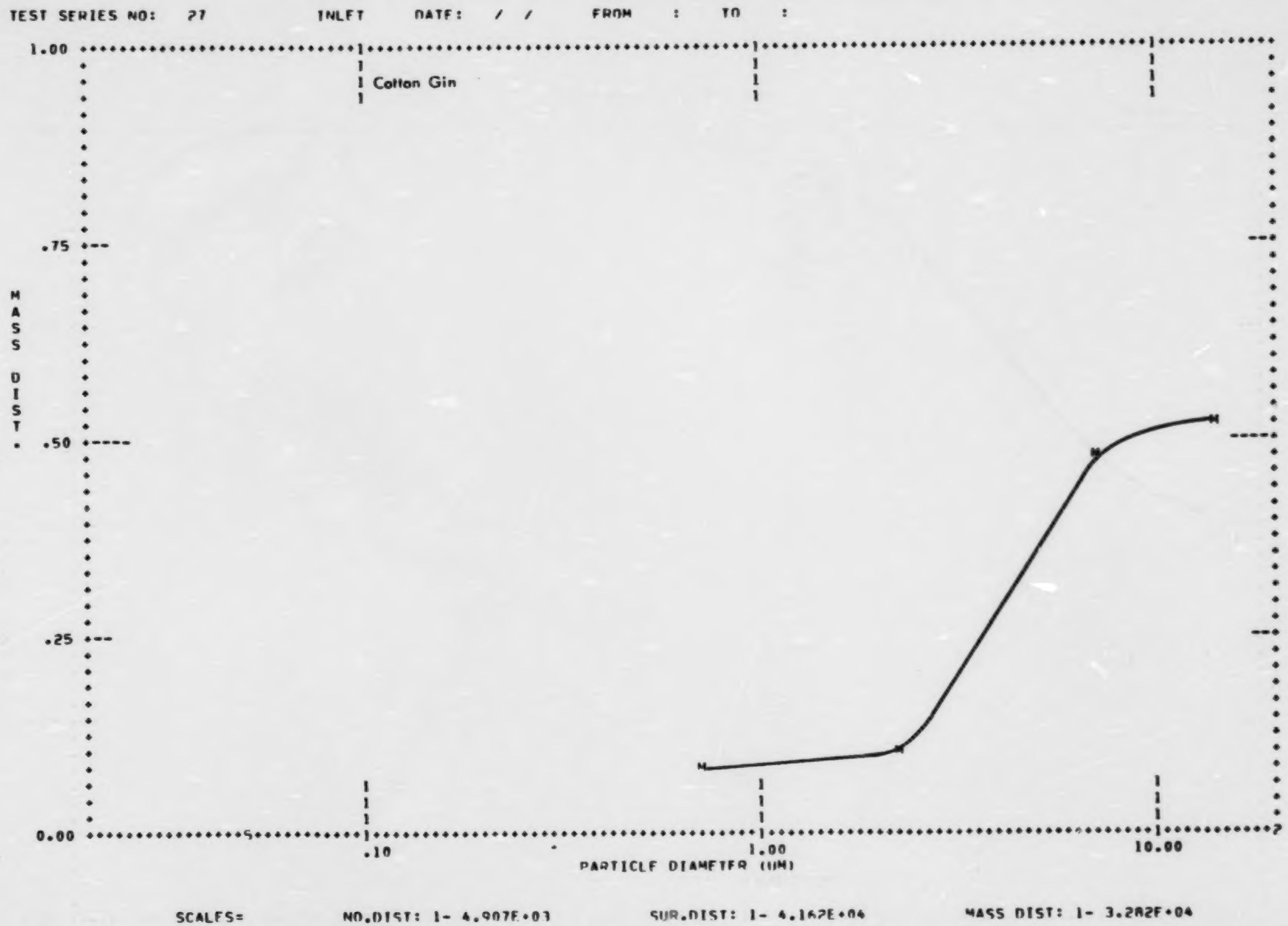

Figure A-50. Inlet Size Distributions of Test Series No. 27

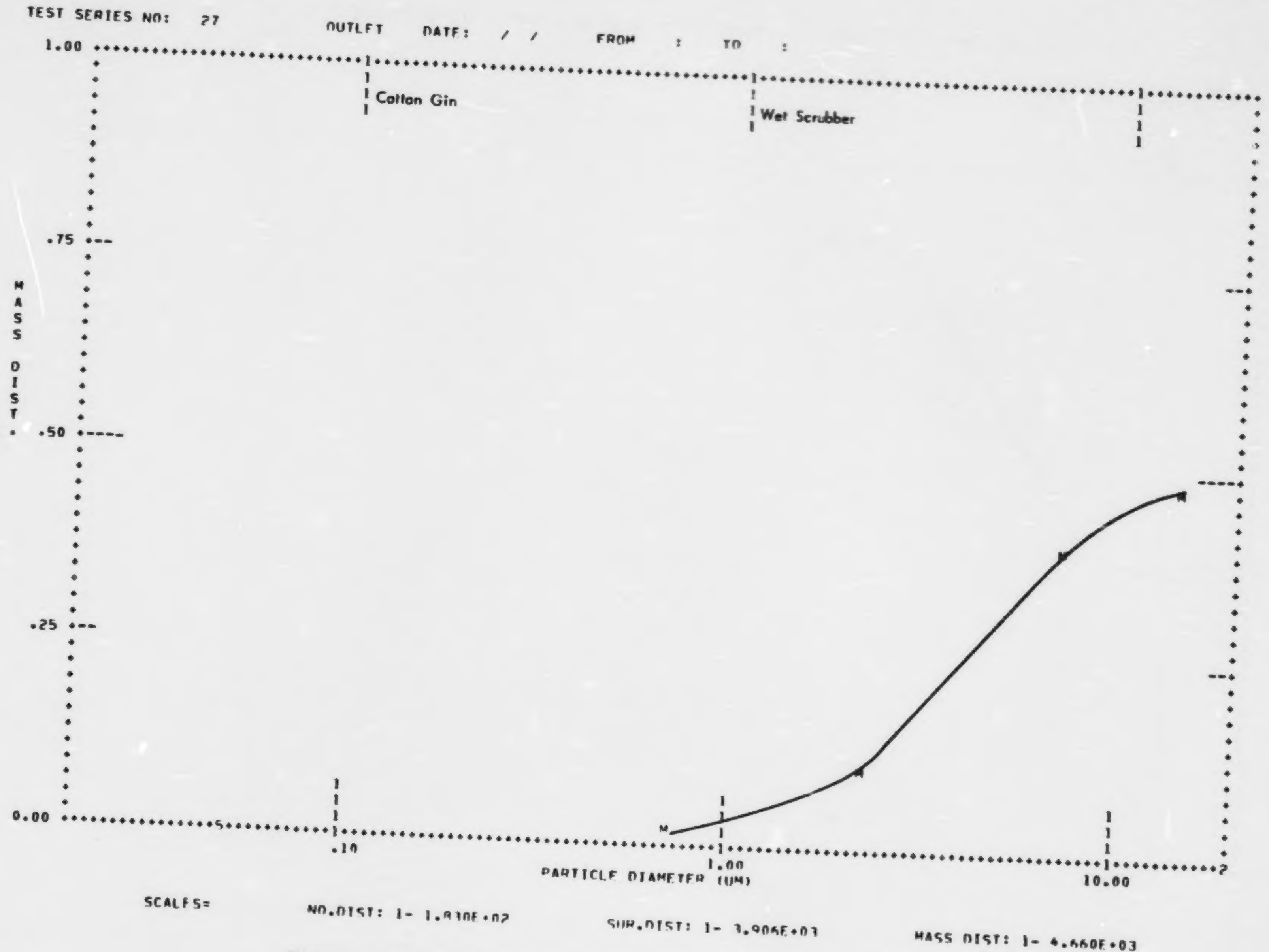

Figure A-51. Outlet Size Distributions of Test Series No. 27

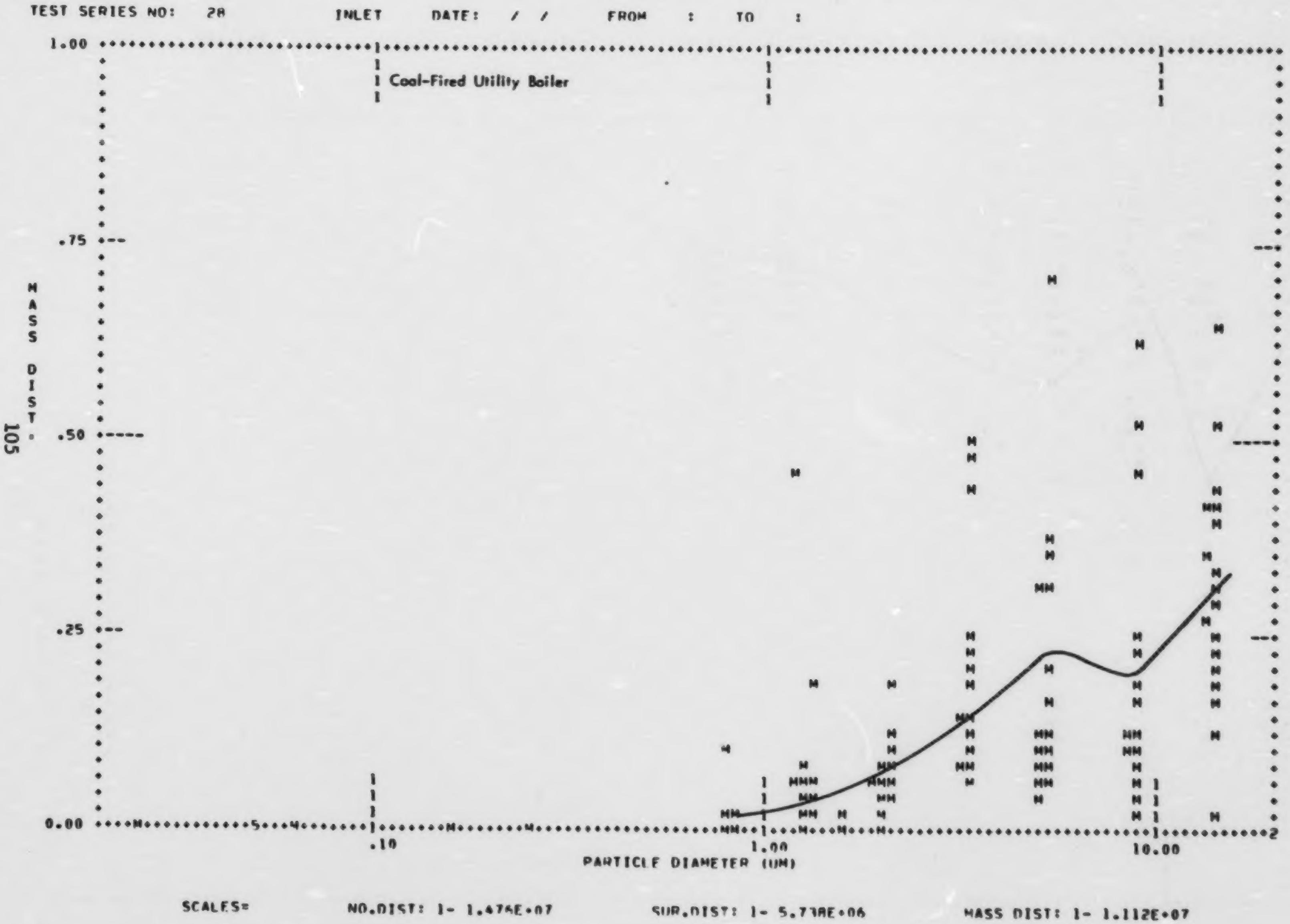

Figure A-52. Inlet Size Distributions of Test Series No. 28

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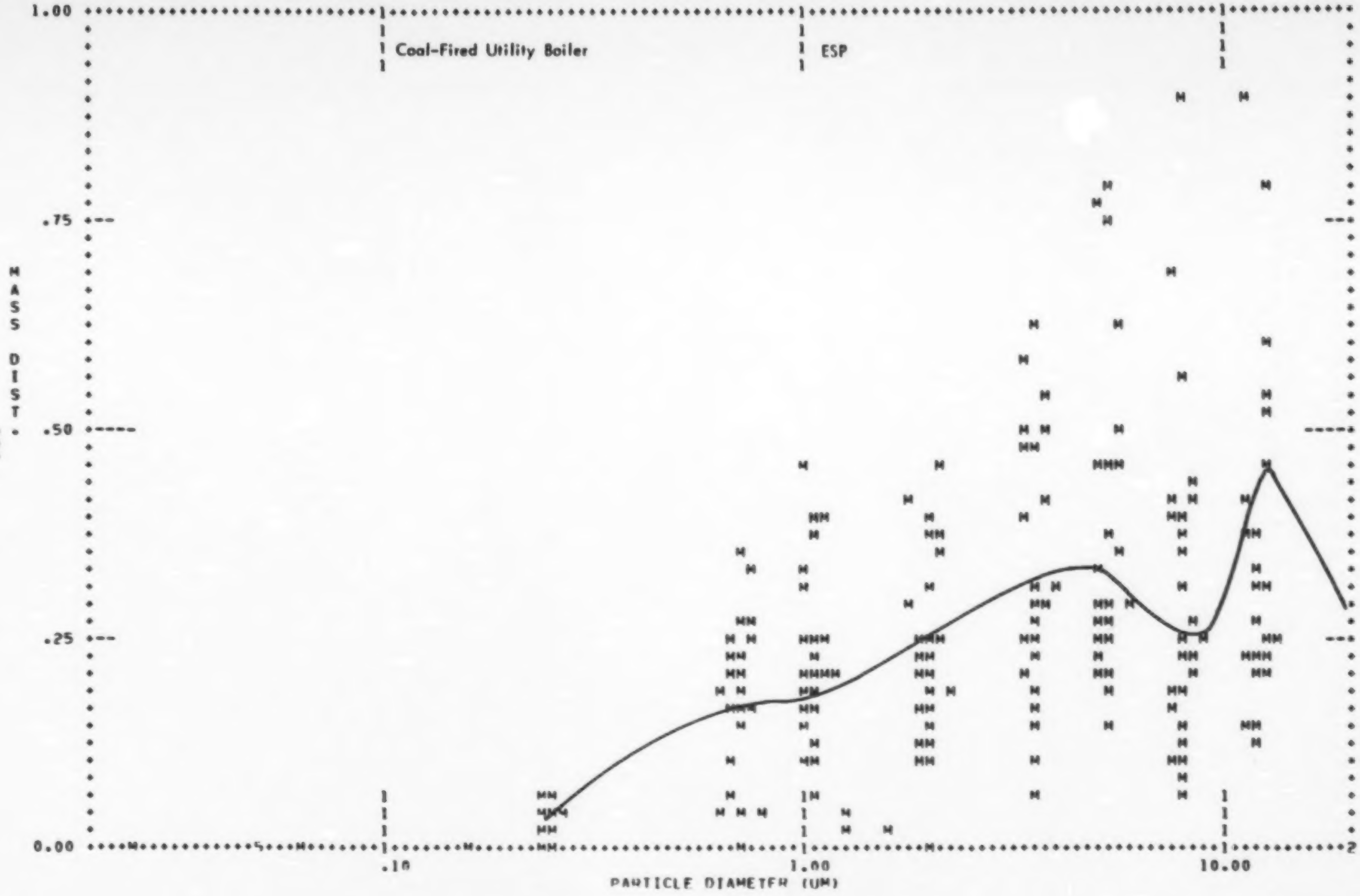
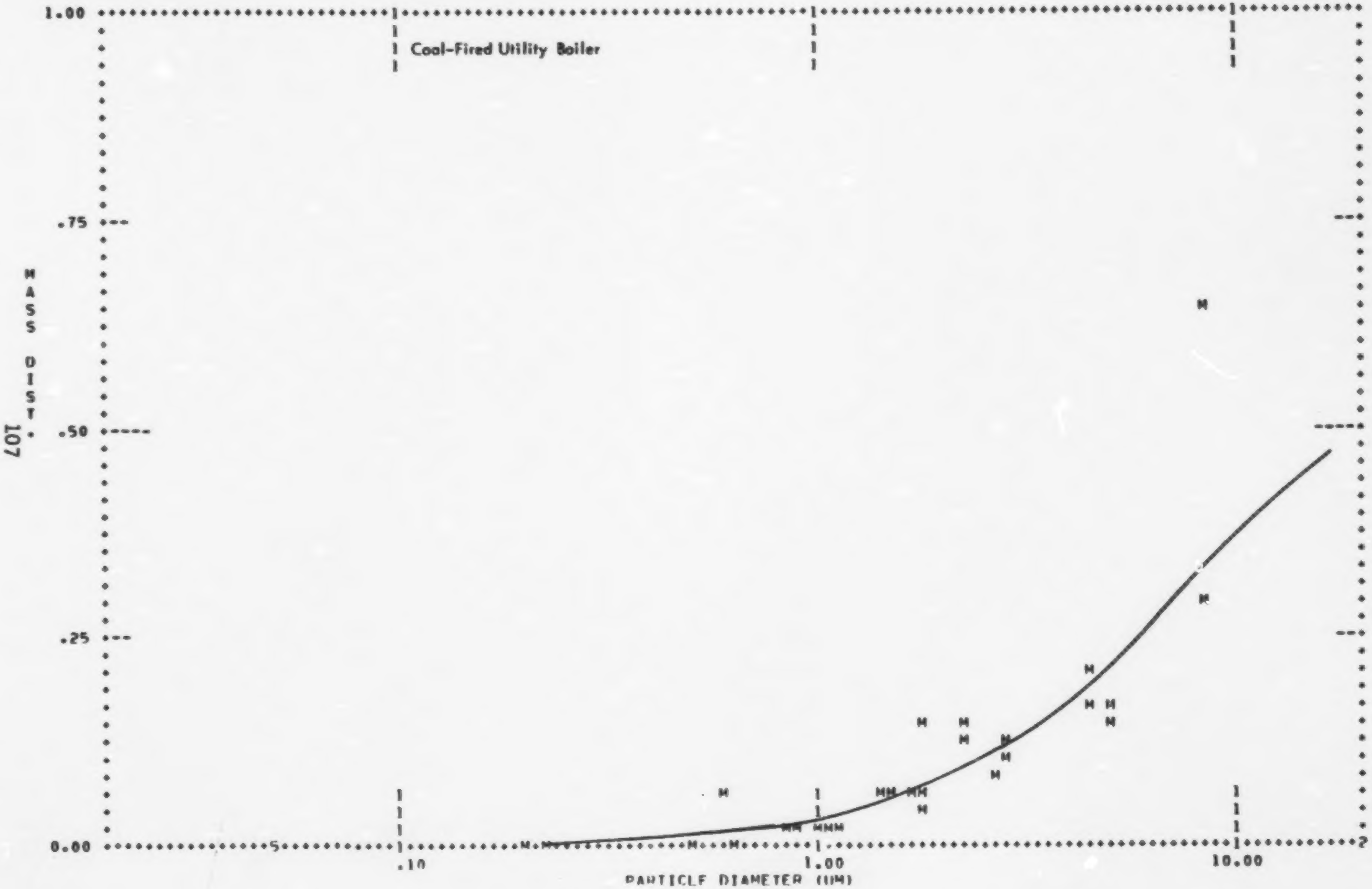


SCALES= NO.DIST: 1- 2.864E+06 SUR.DIST: 1- 7.252E+05 MASS DIST: 1- 3.865E+05

Figure A-53. Outlet Size Distributions of Test Series No. 28

TEST SERIES NO: 29 INLET DATE: / / FROM : TO :



SCALES= NO.DIST: 1- 2.707E+06 SUR.DIST: 1- 2.990E+06 MASS DIST: 1- 4.234E+06

Figure A-54. Inlet Size Distributions of Test Series No. 29

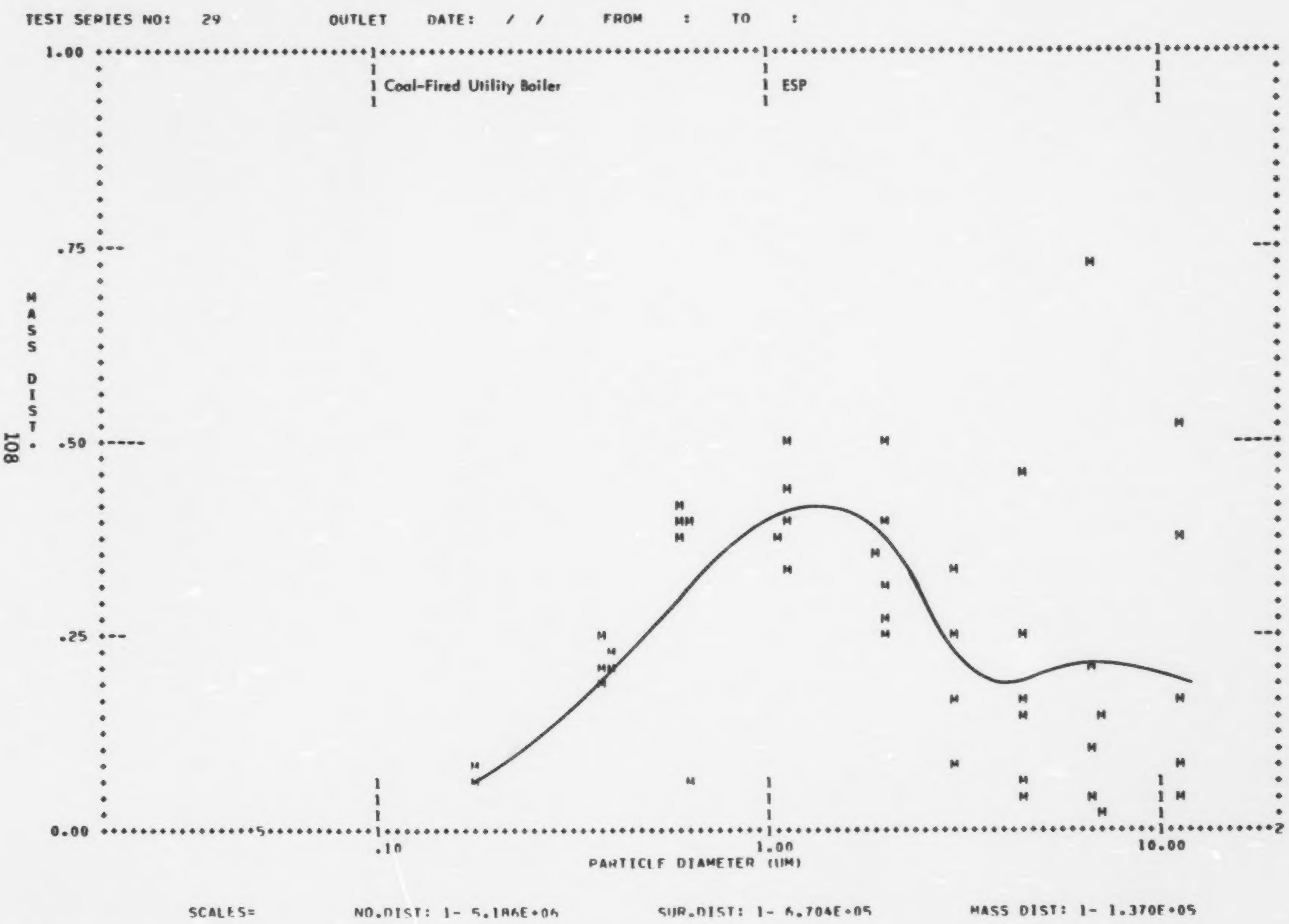


Figure A-55. Outlet Size Distributions of Test Series No. 29

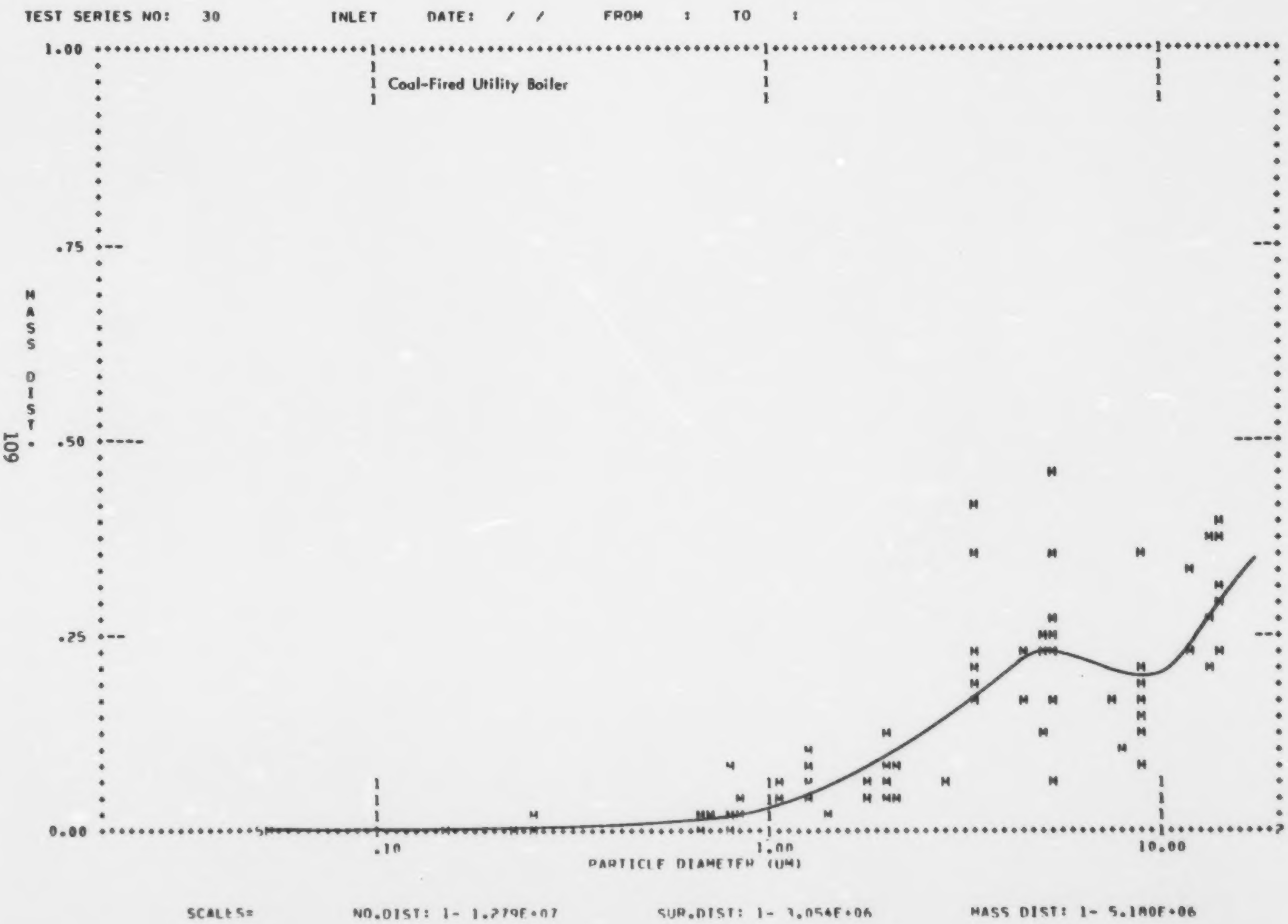


Figure A-56. Inlet Size Distributions of Test Series No. 30

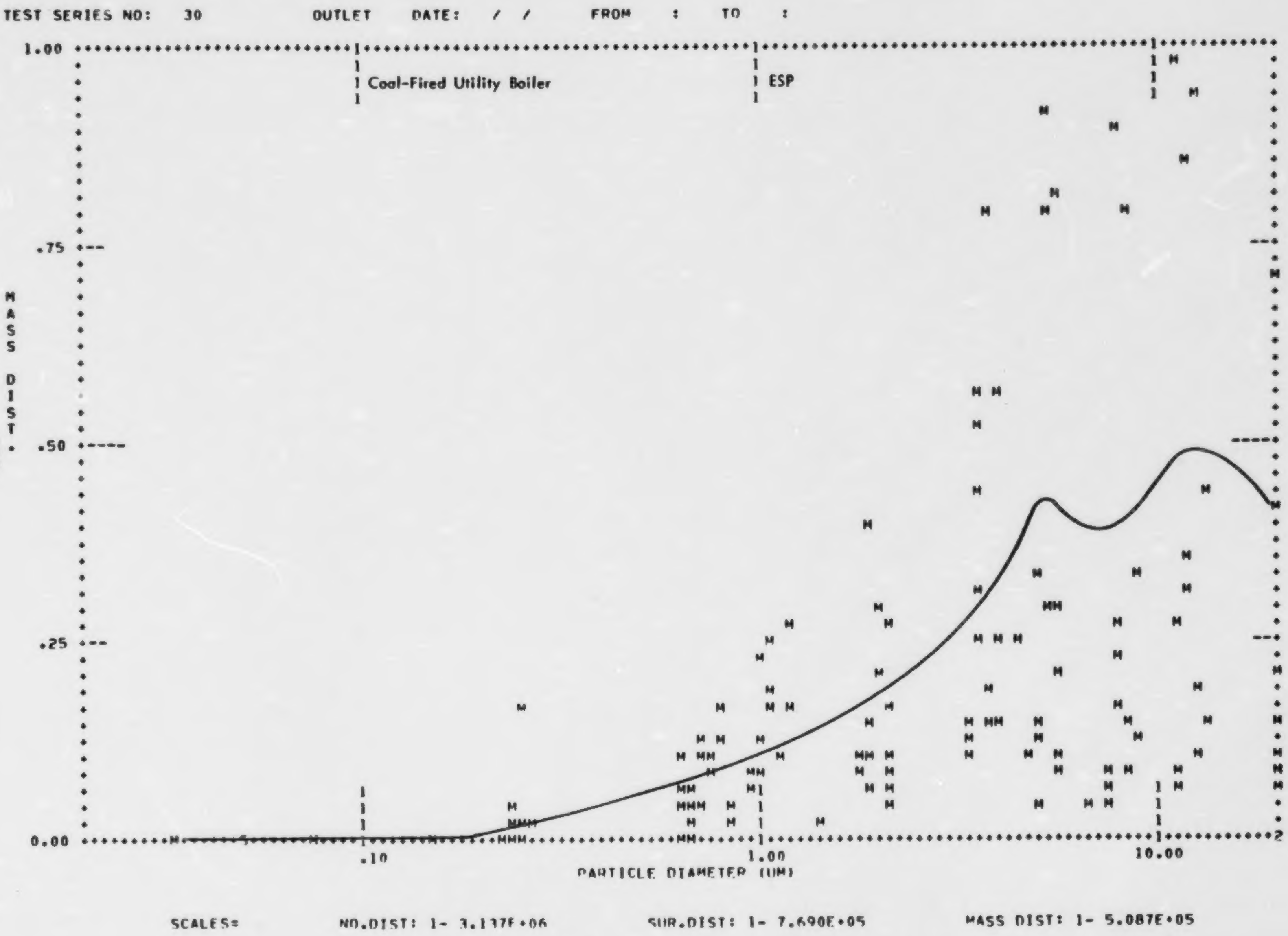


Figure A-57. Outlet Size Distributions of Test Series No. 30

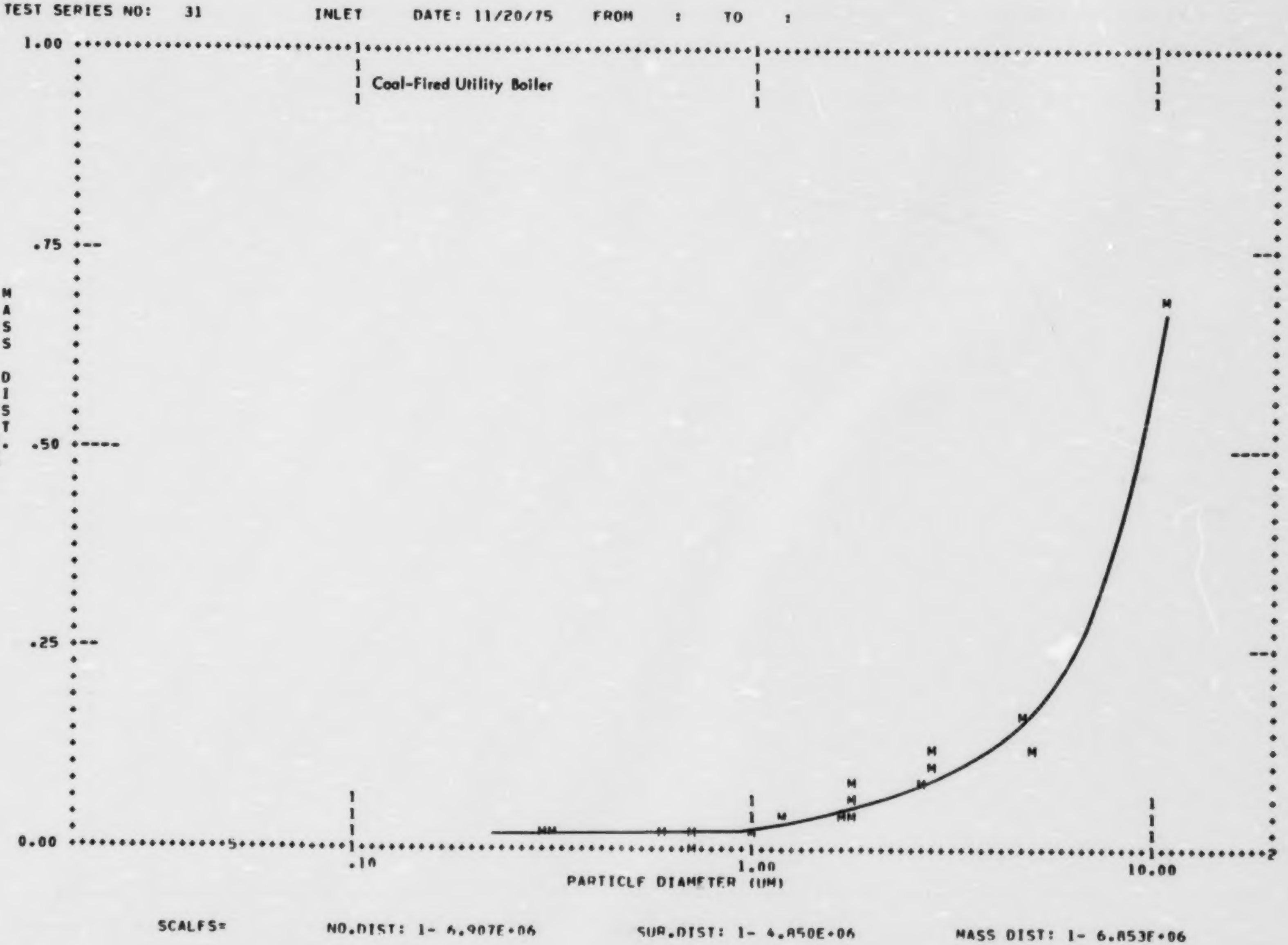


Figure A-58. Inlet Size Distributions of Test Series No. 31

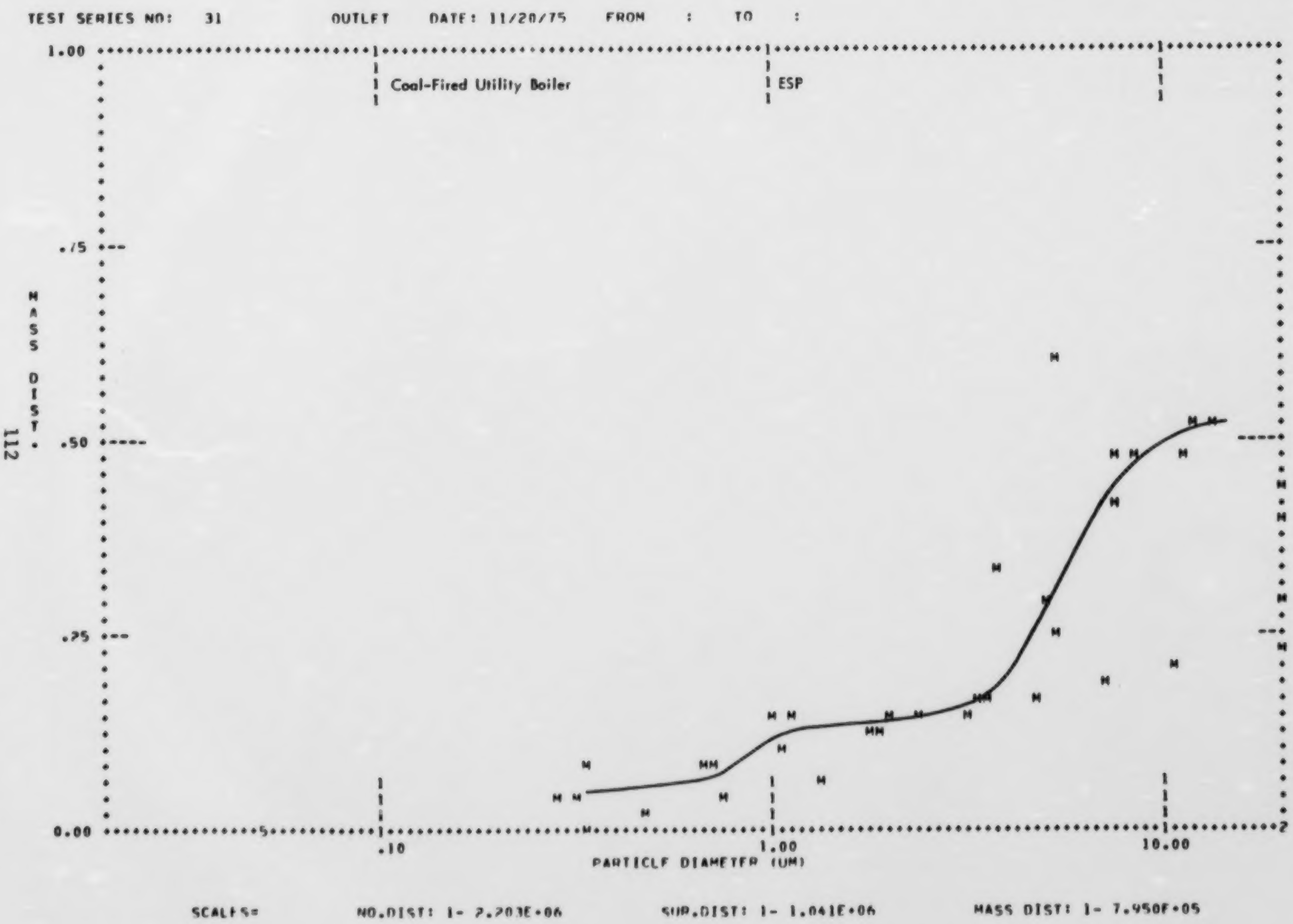


Figure A-59. Outlet Size Distributions of Test Series No. 31

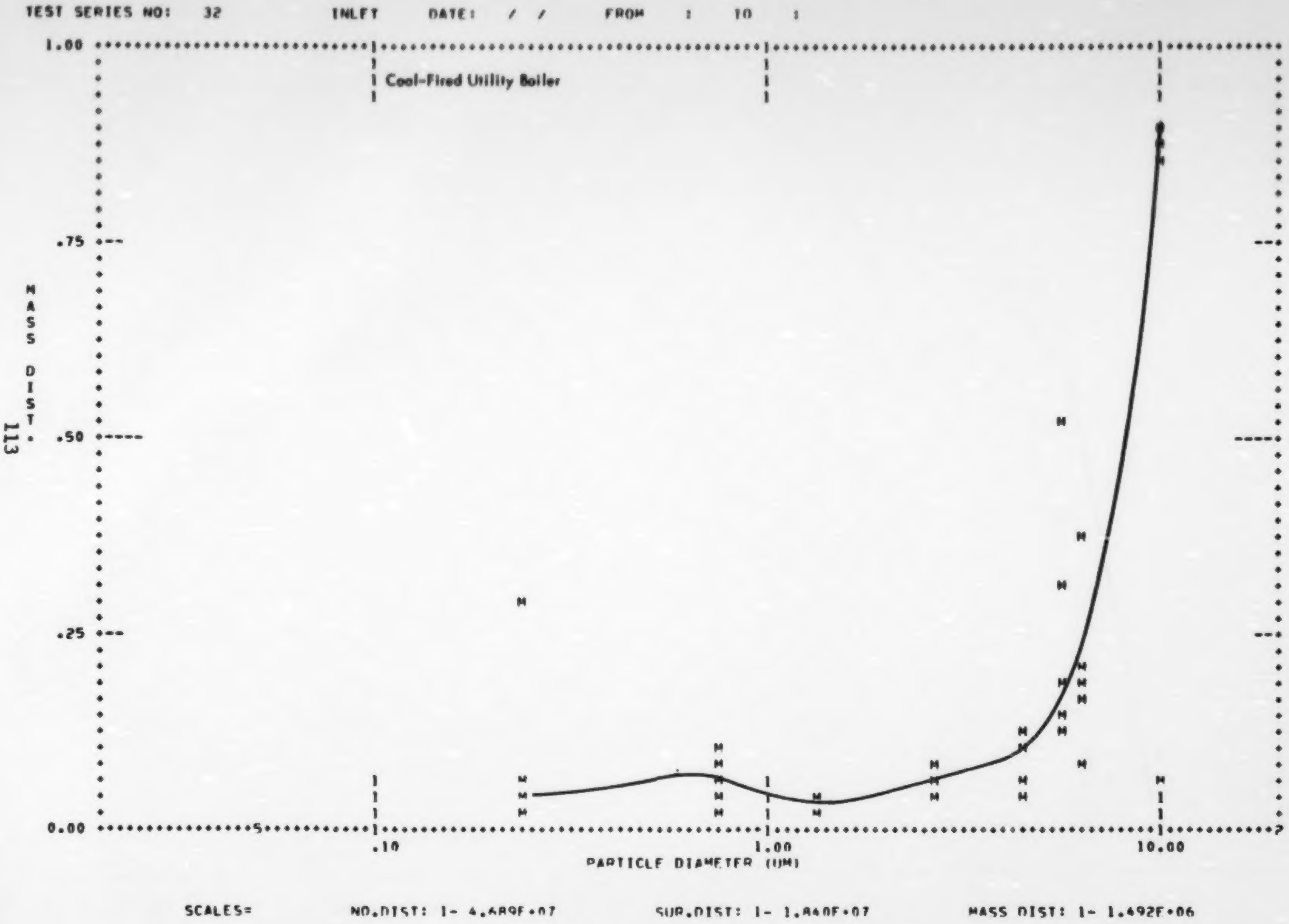


Figure A-60. Inlet Size Distributions of Test Series No. 32

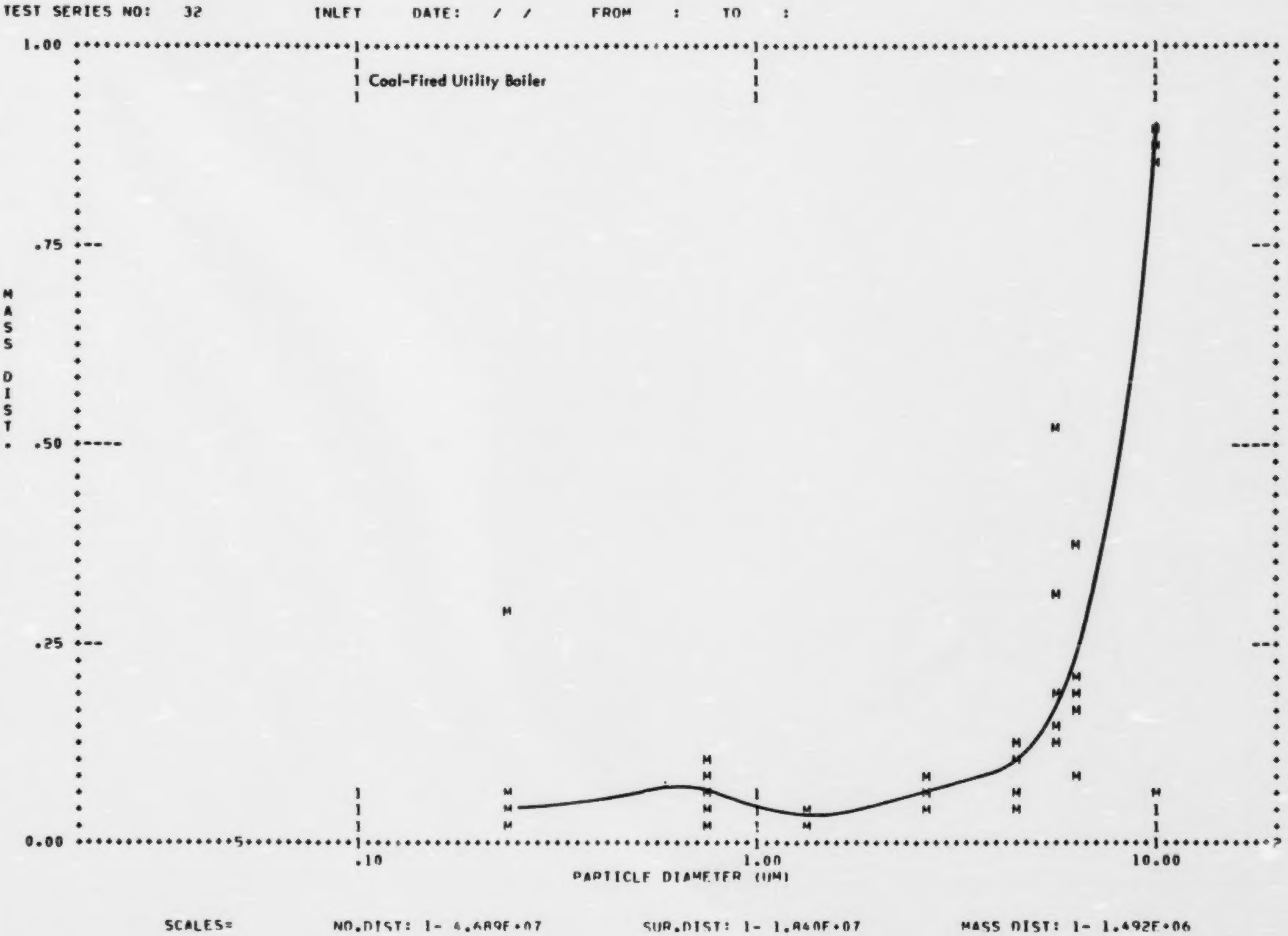


Figure A-60. Inlet Size Distributions of Test Series No. 32

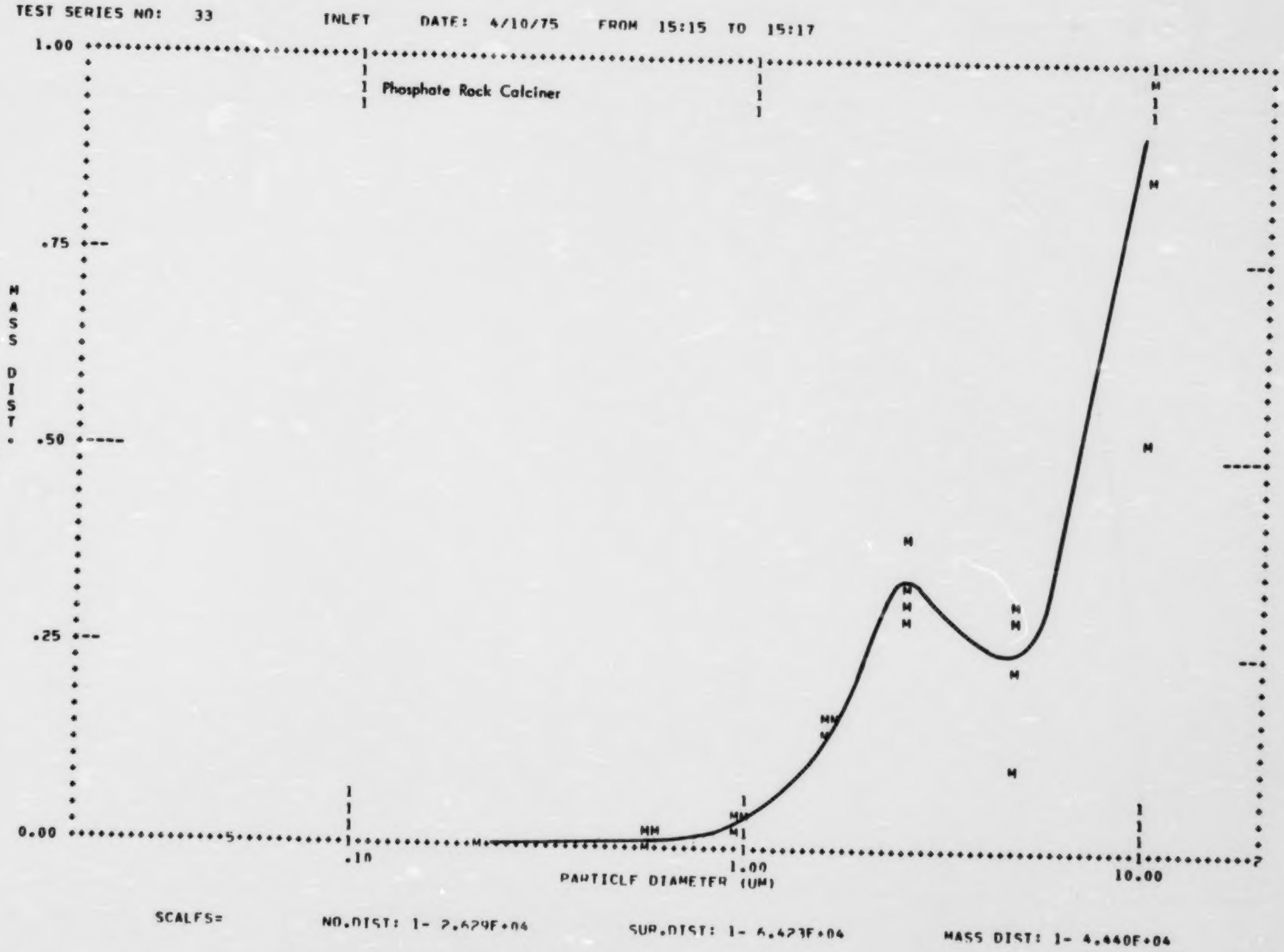


Figure A-61. Inlet Size Distributions of Test Series No. 33

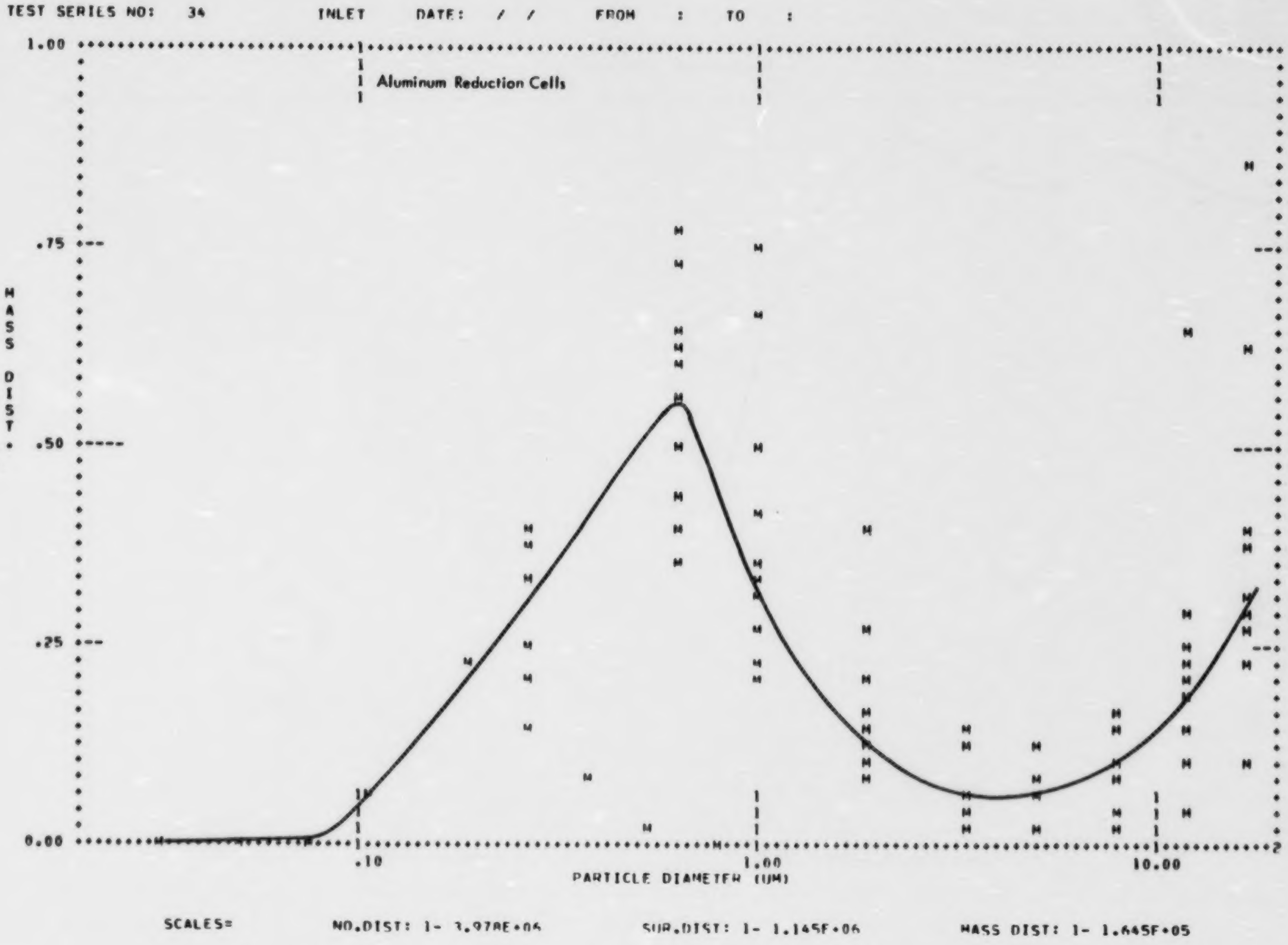


Figure A-62. Inlet Size Distributions of Test Series No. 34

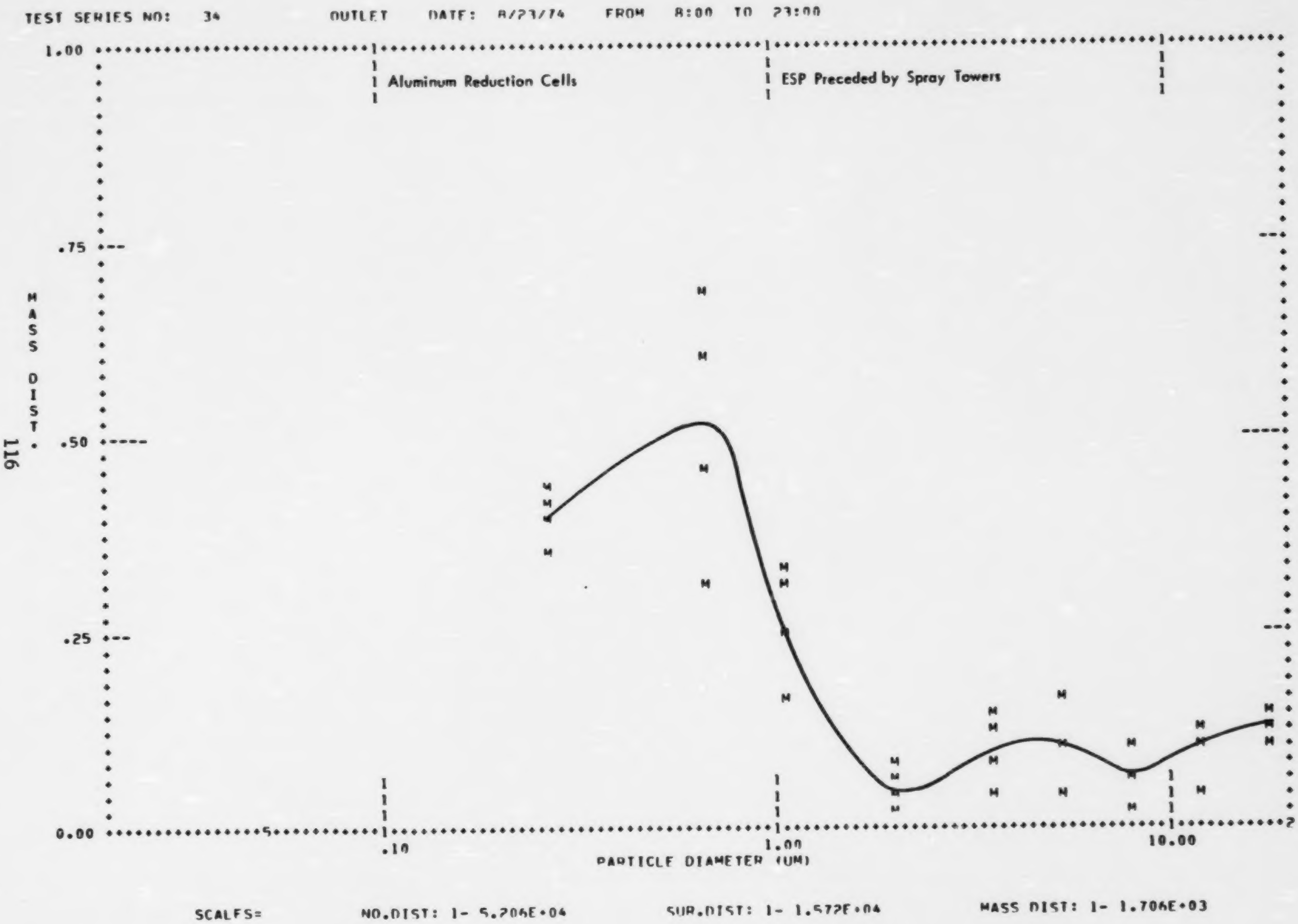


Figure A-63. Outlet Size Distributions of Test Series No. 34

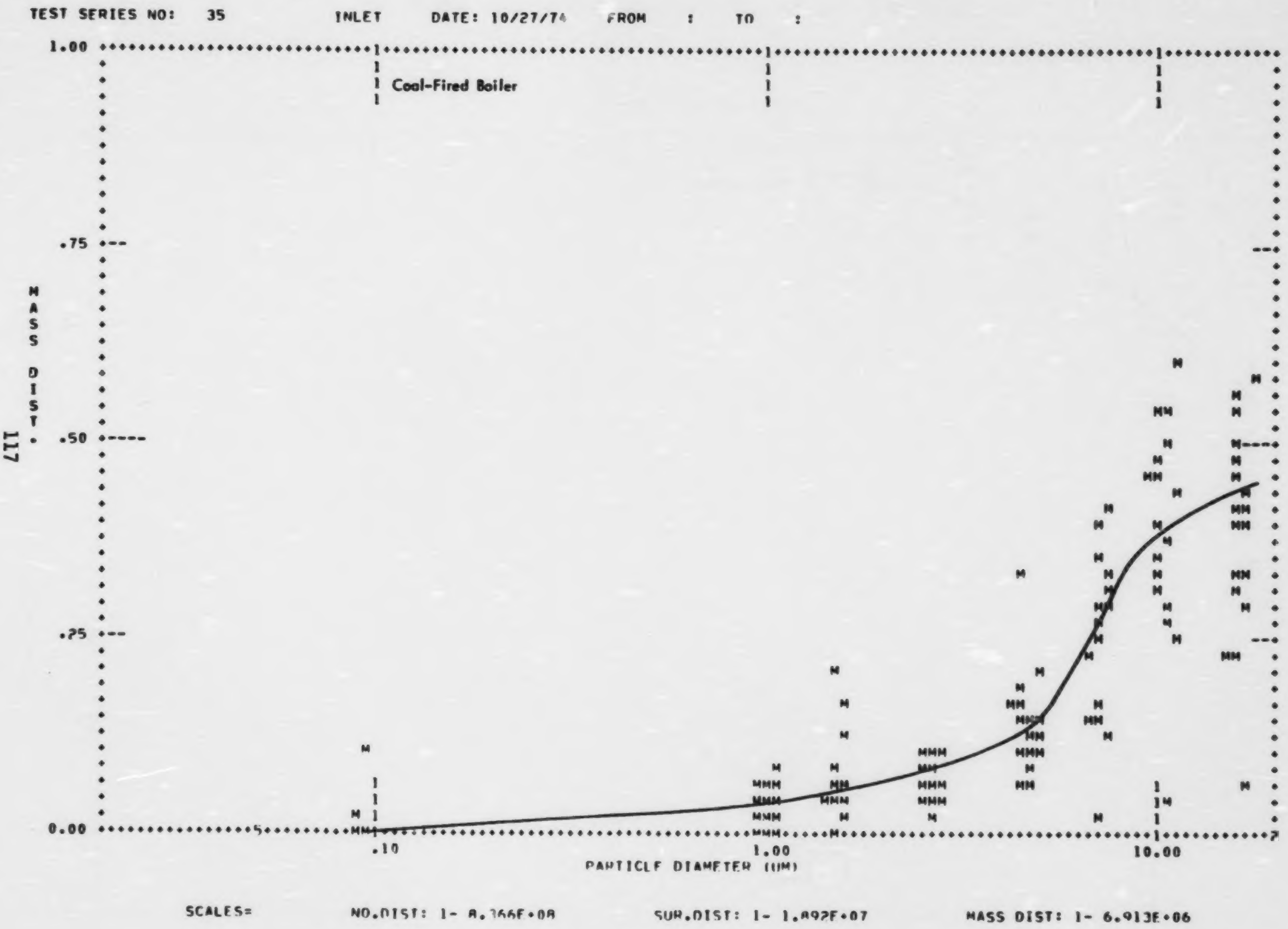


Figure A-64. Inlet Size Distributions of Test Series No. 35

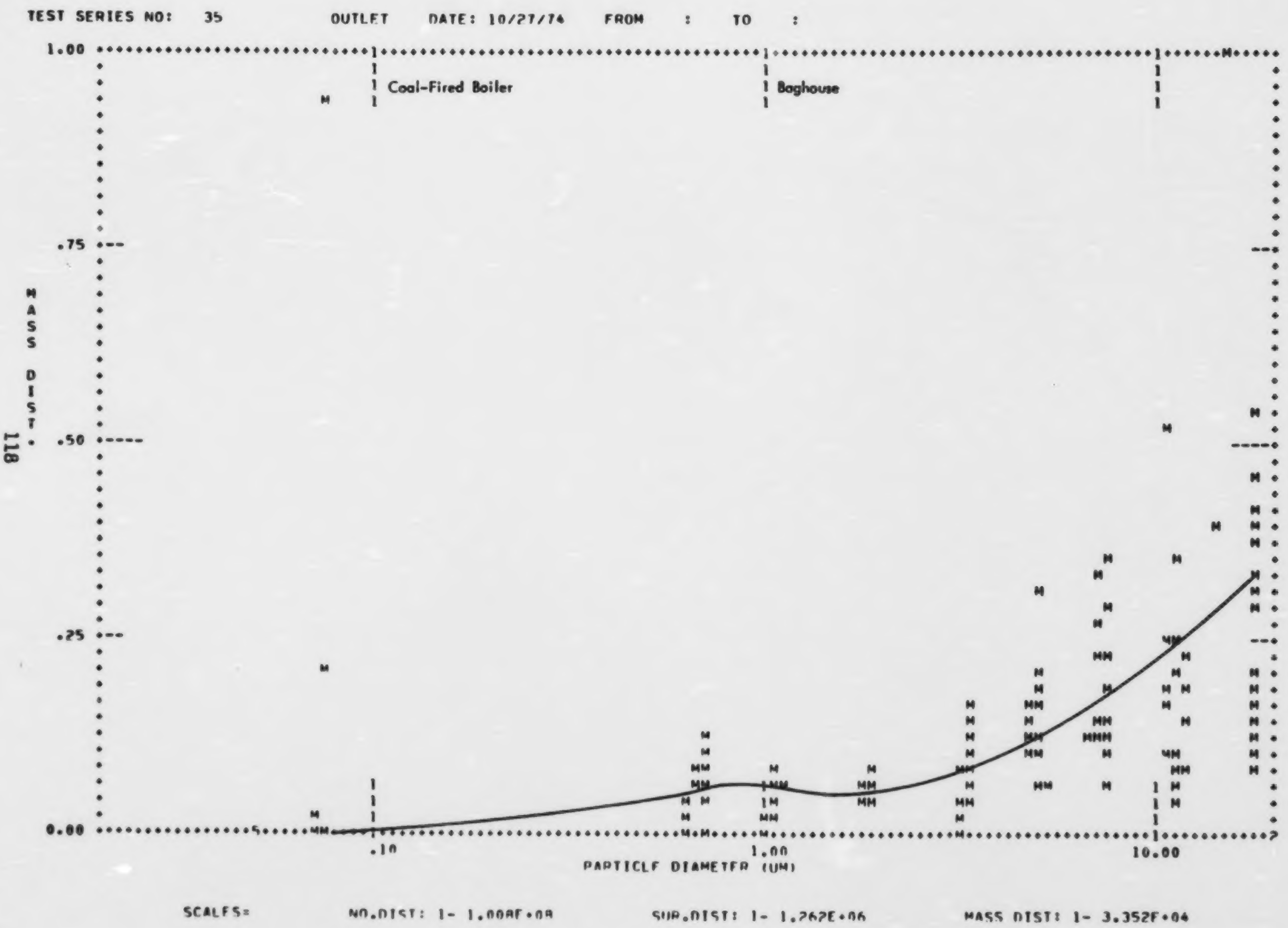


Figure A-65. Outlet Size Distributions of Test Series No. 35

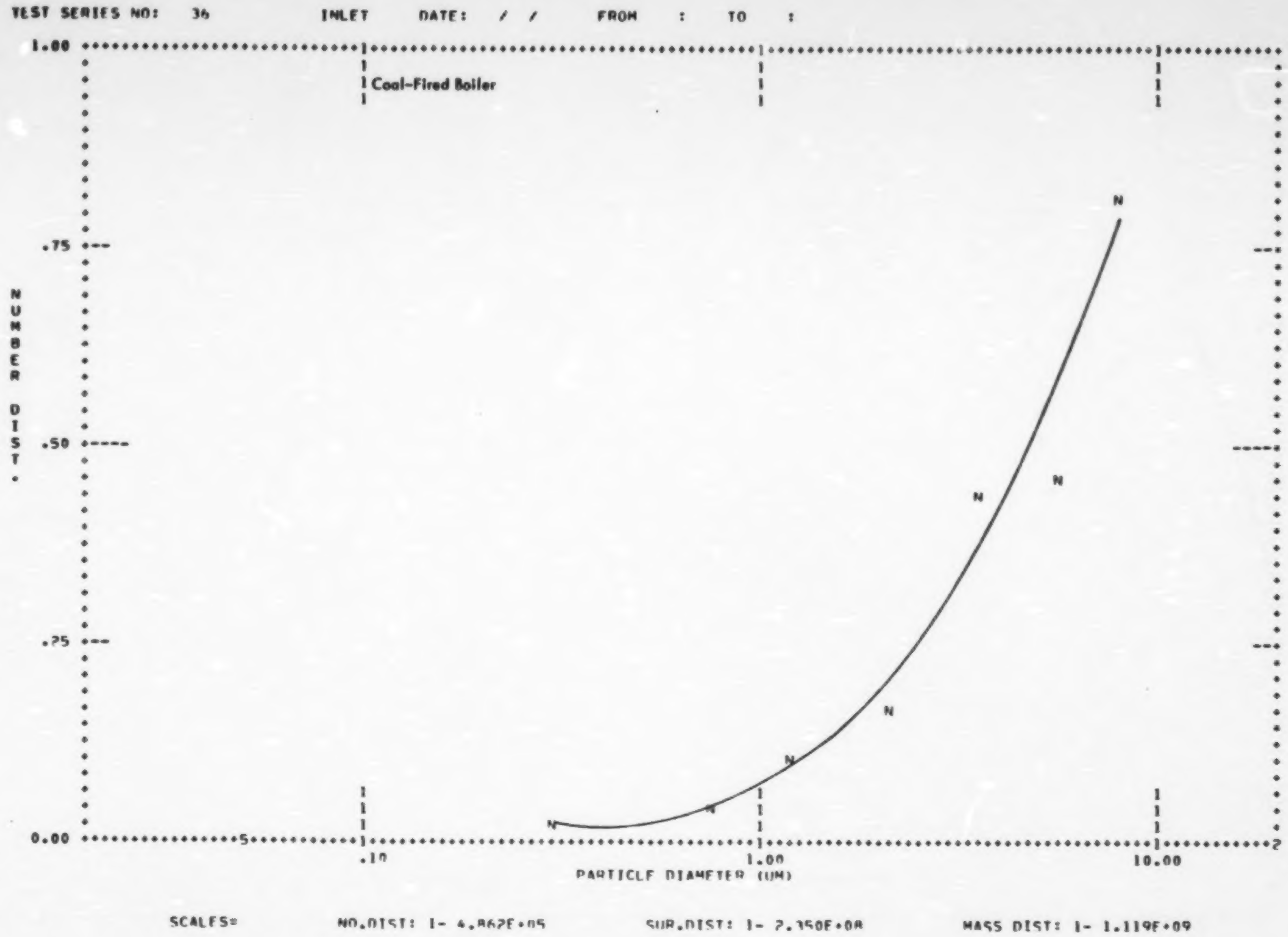
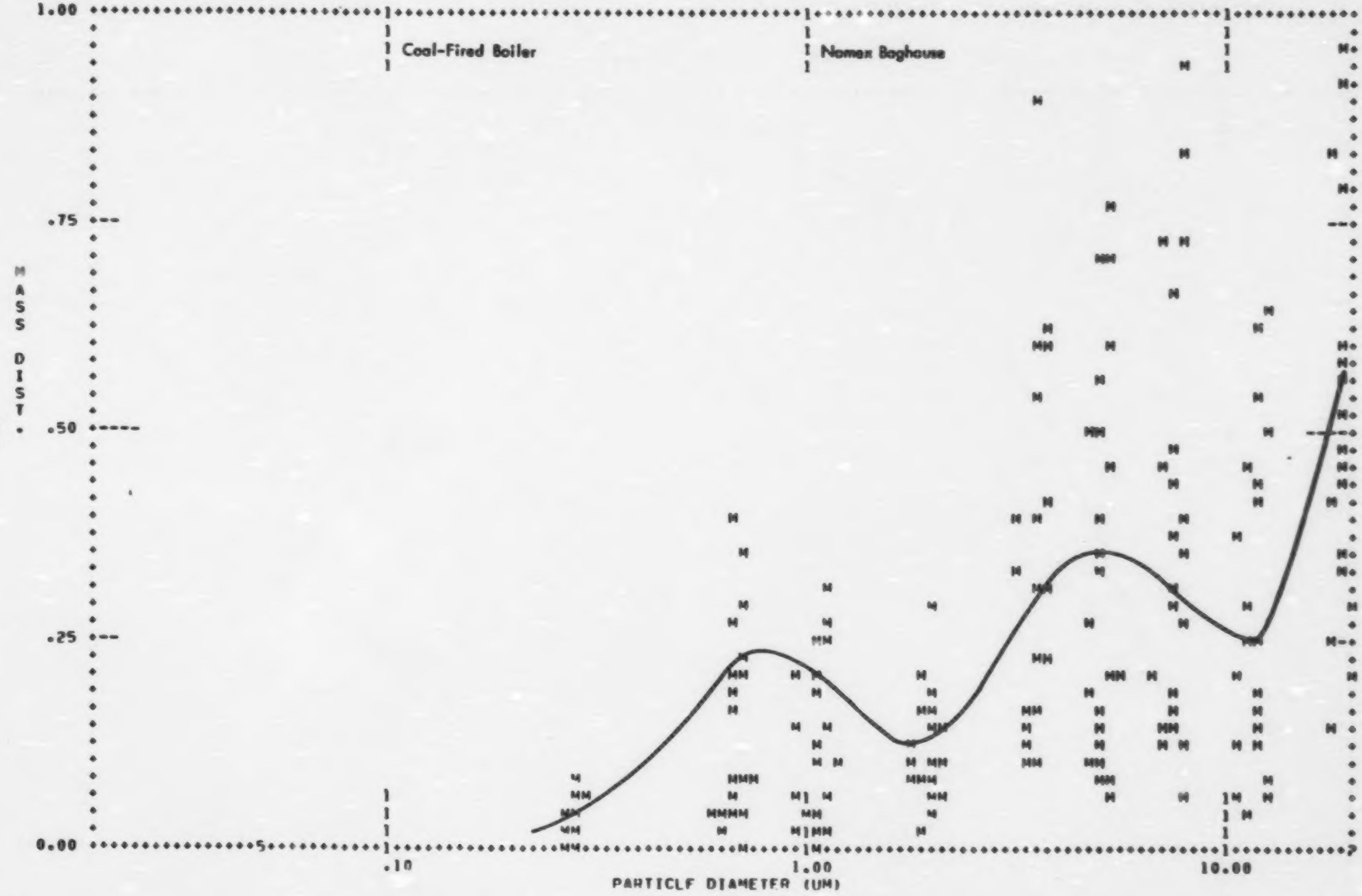


Figure A-66. Inlet Size Distributions of Test Series No. 36

TEST SERIES NO: 36 OUTLET DATE: 8/21/74 FROM 10:05 TO :



SCALES= NO.DIST: 1- 4.927E+04 SUR.DIST: 1- 3.339E+04 MASS DIST: 1- 2.495E+04

Figure A-67. Outlet Size Distributions of Test Series No. 36

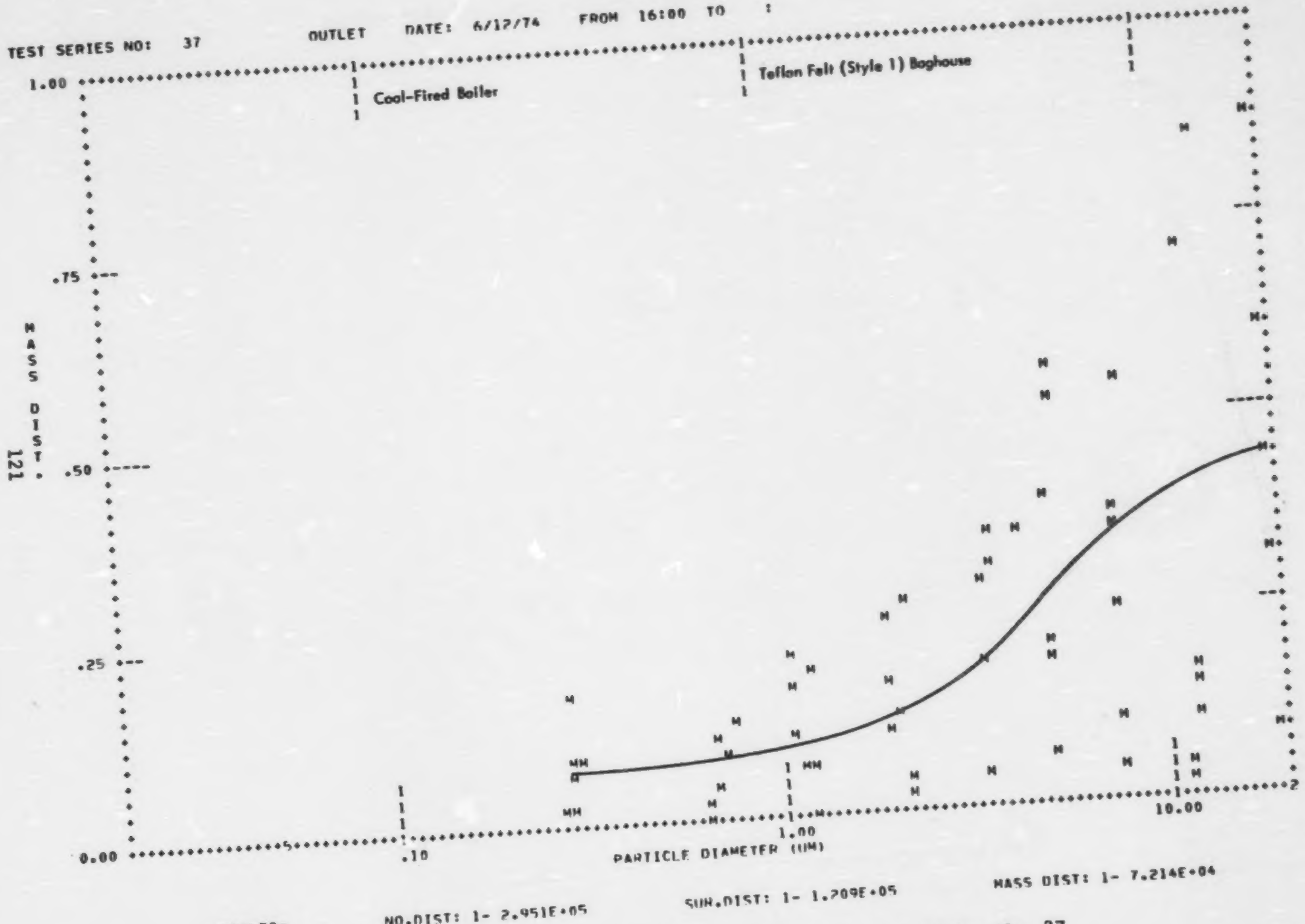


Figure A-68. Outlet Size Distributions of Test Series No. 37

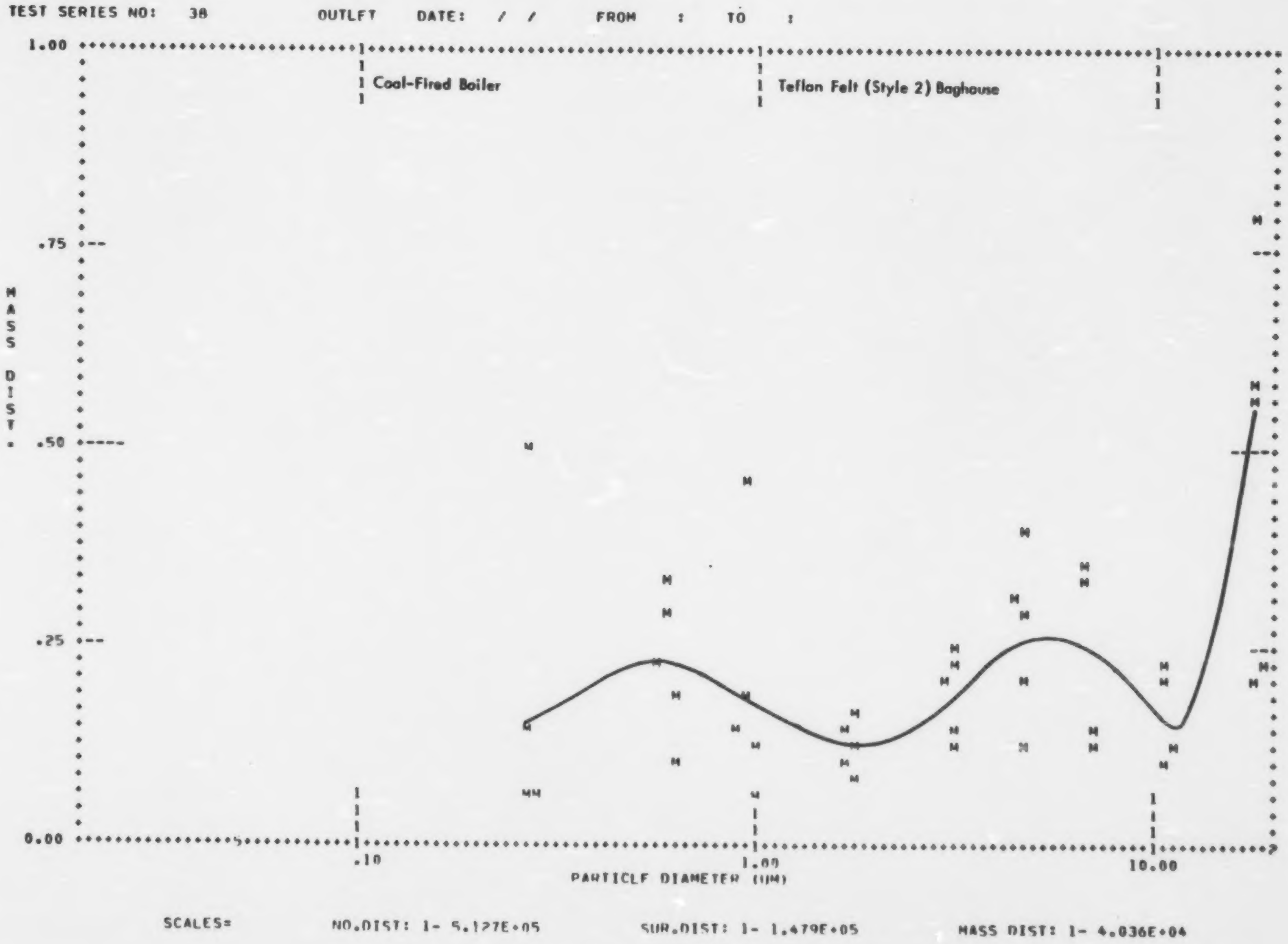


Figure A-69. Outlet Size Distributions of Test Series No. 38

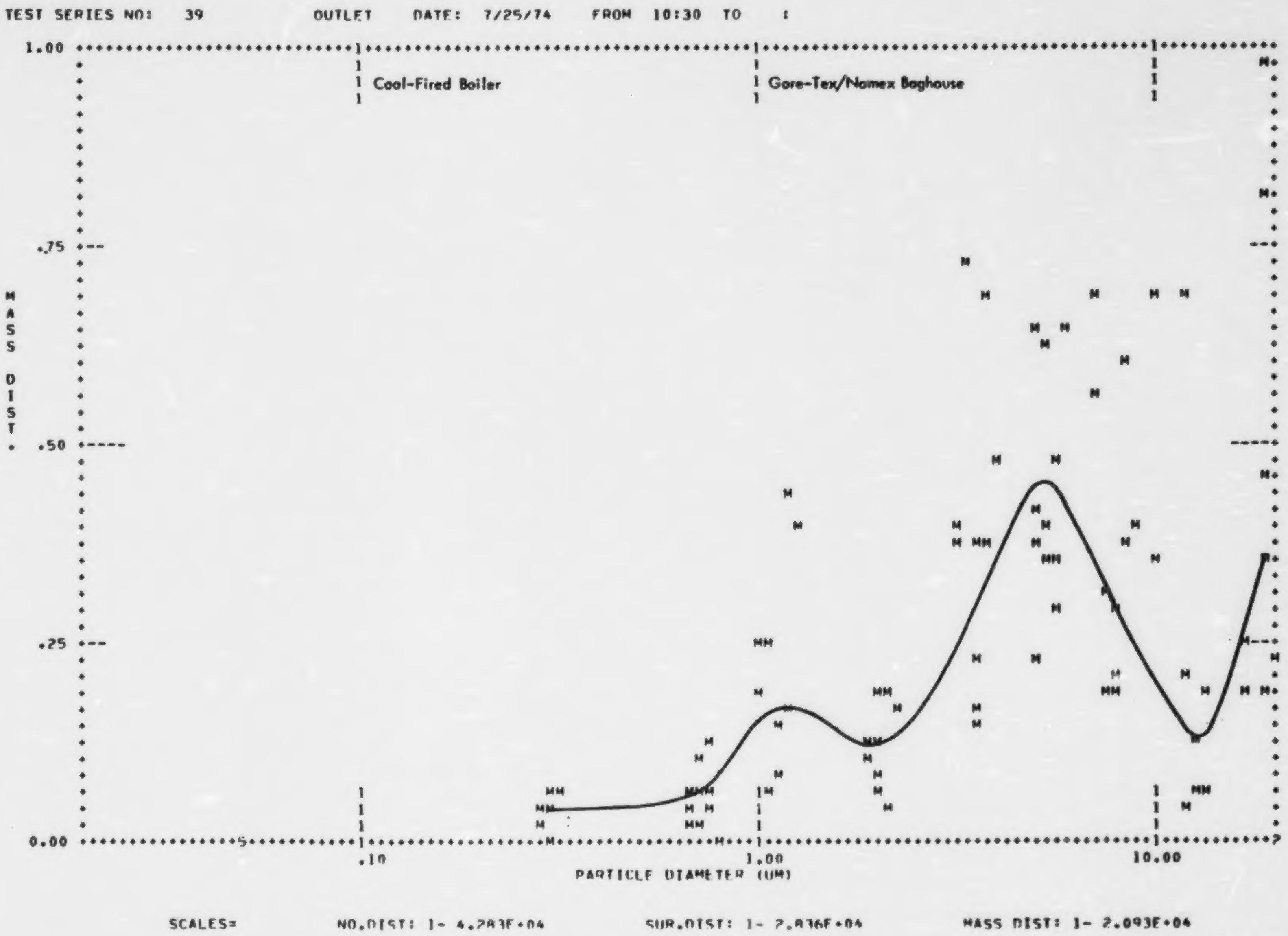


Figure A-70. Outlet Size Distributions of Test Series No. 39

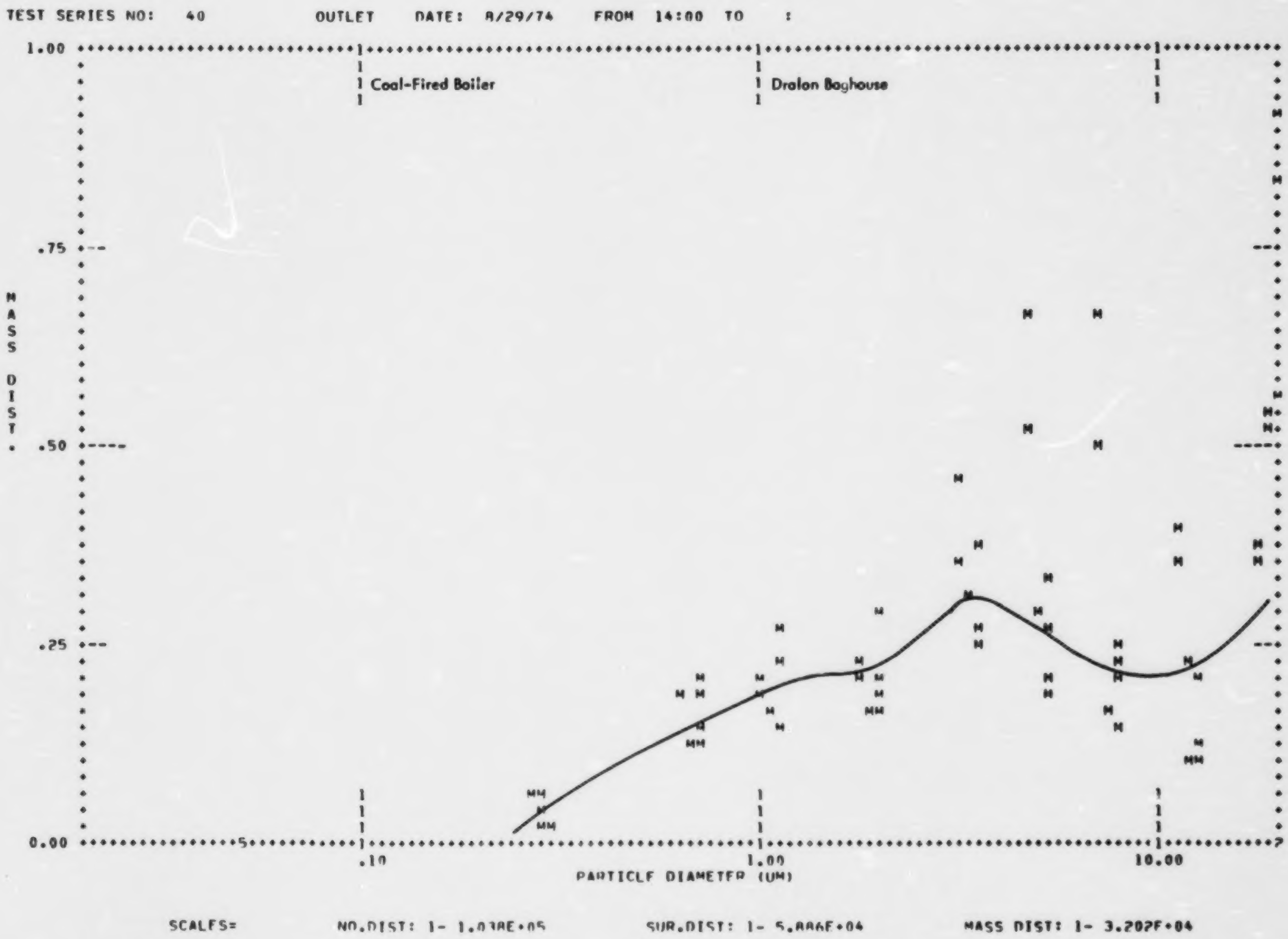


Figure A-71. Outlet Size Distributions of Test Series No. 40

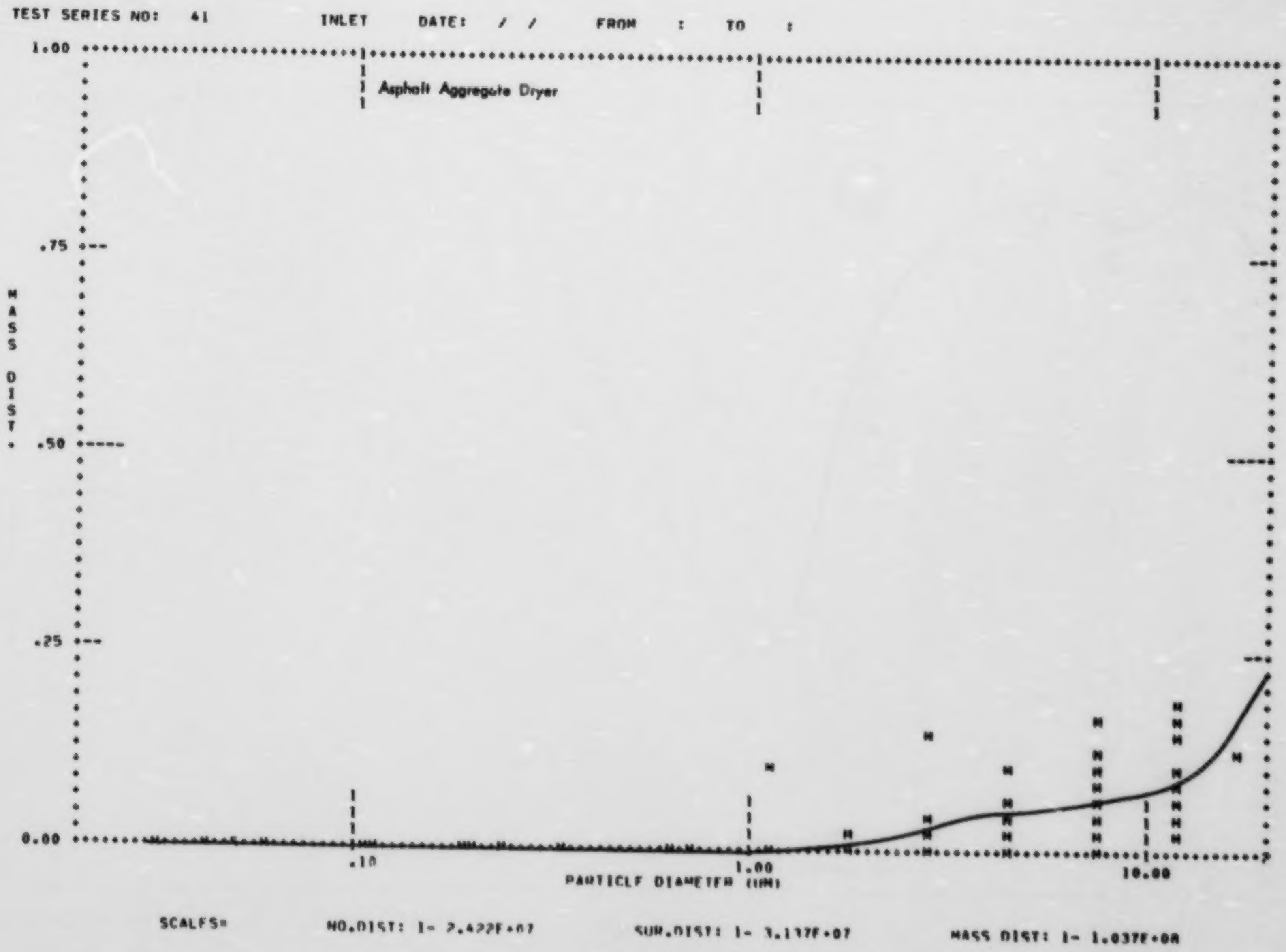


Figure A-72. Inlet Size Distributions of Test Series No. 41

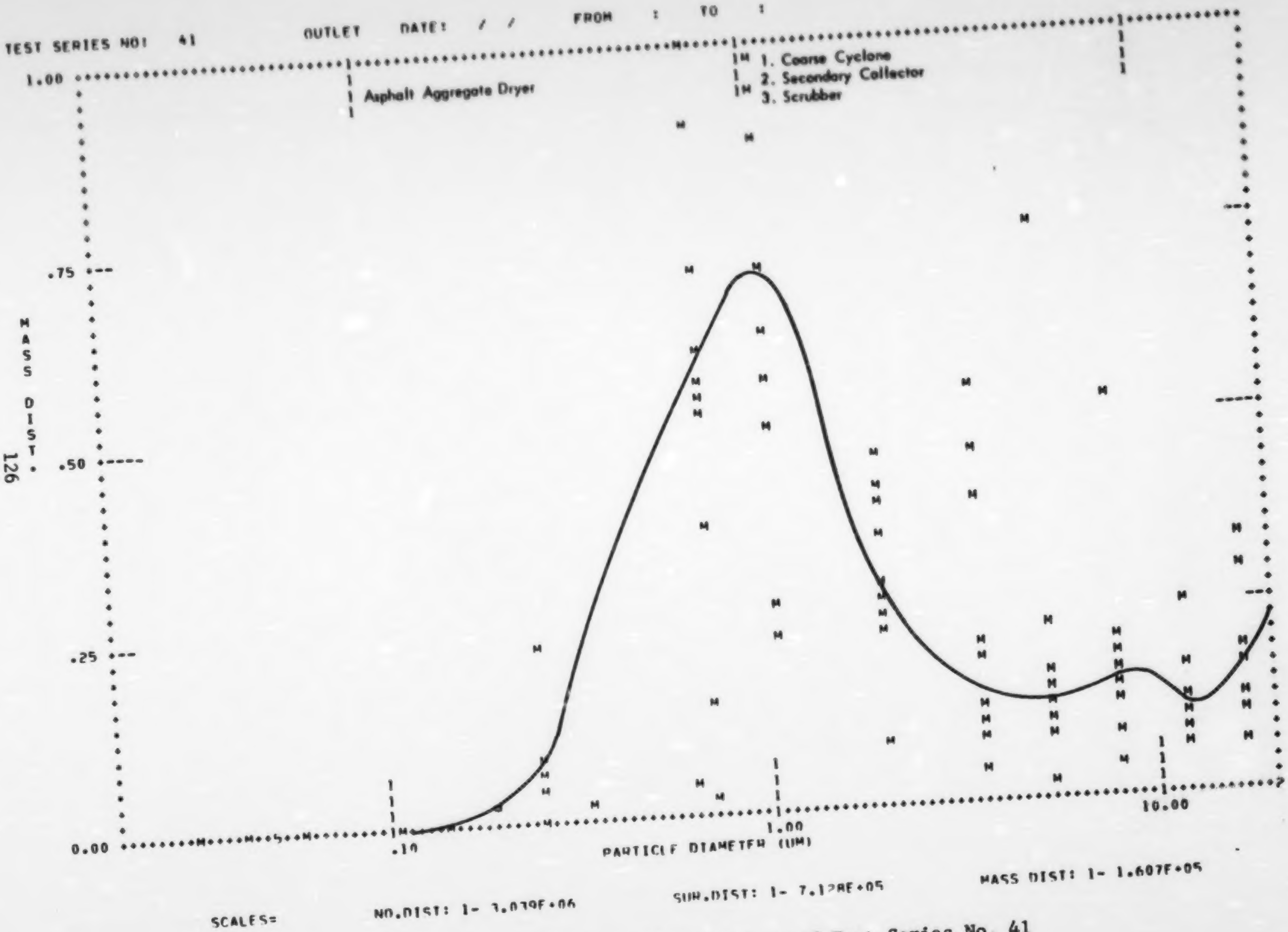


Figure A-73. Outlet Size Distributions of Test Series No. 41

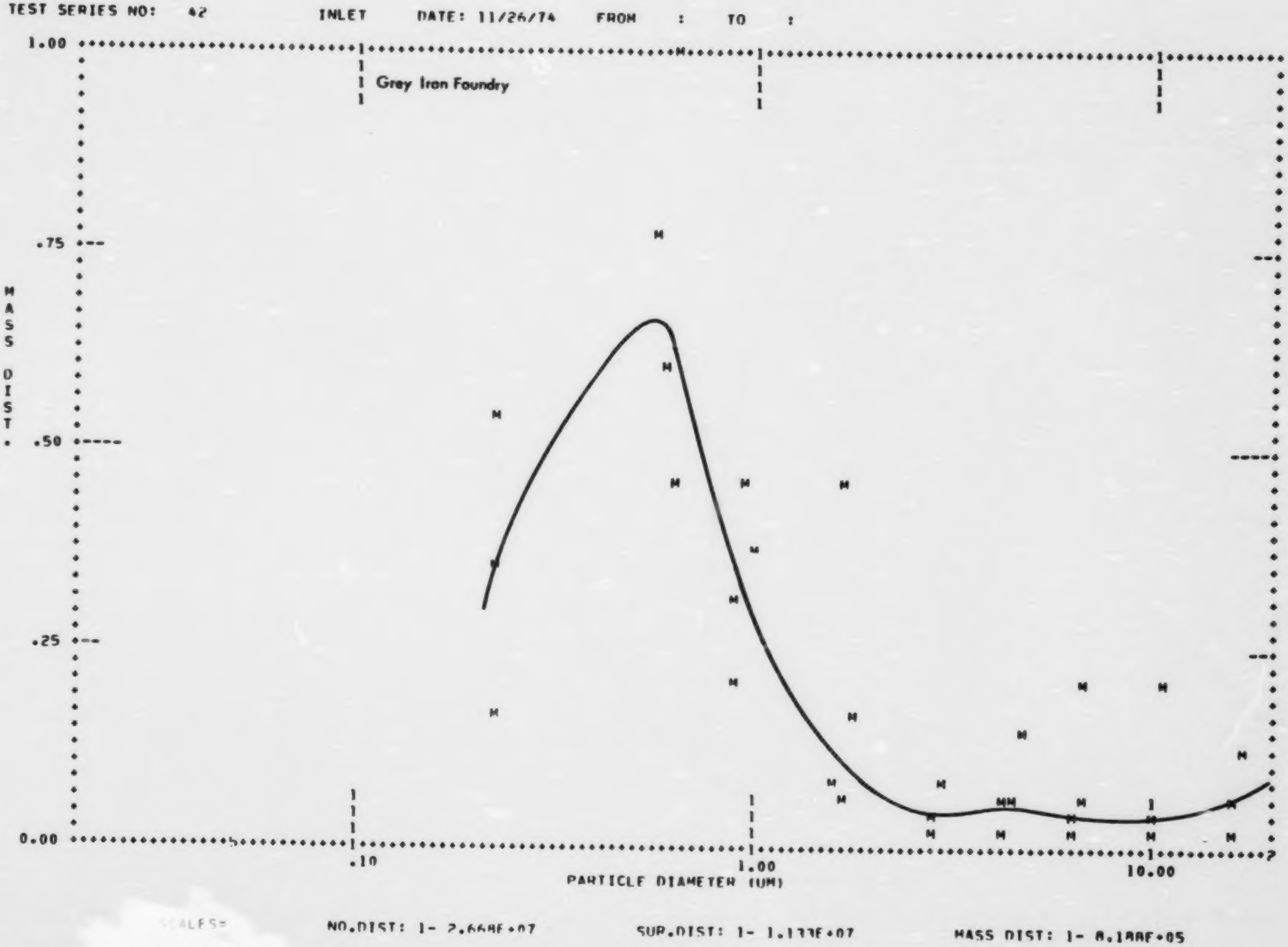


Figure A-74. Inlet Size Distributions of Test Series No. 42

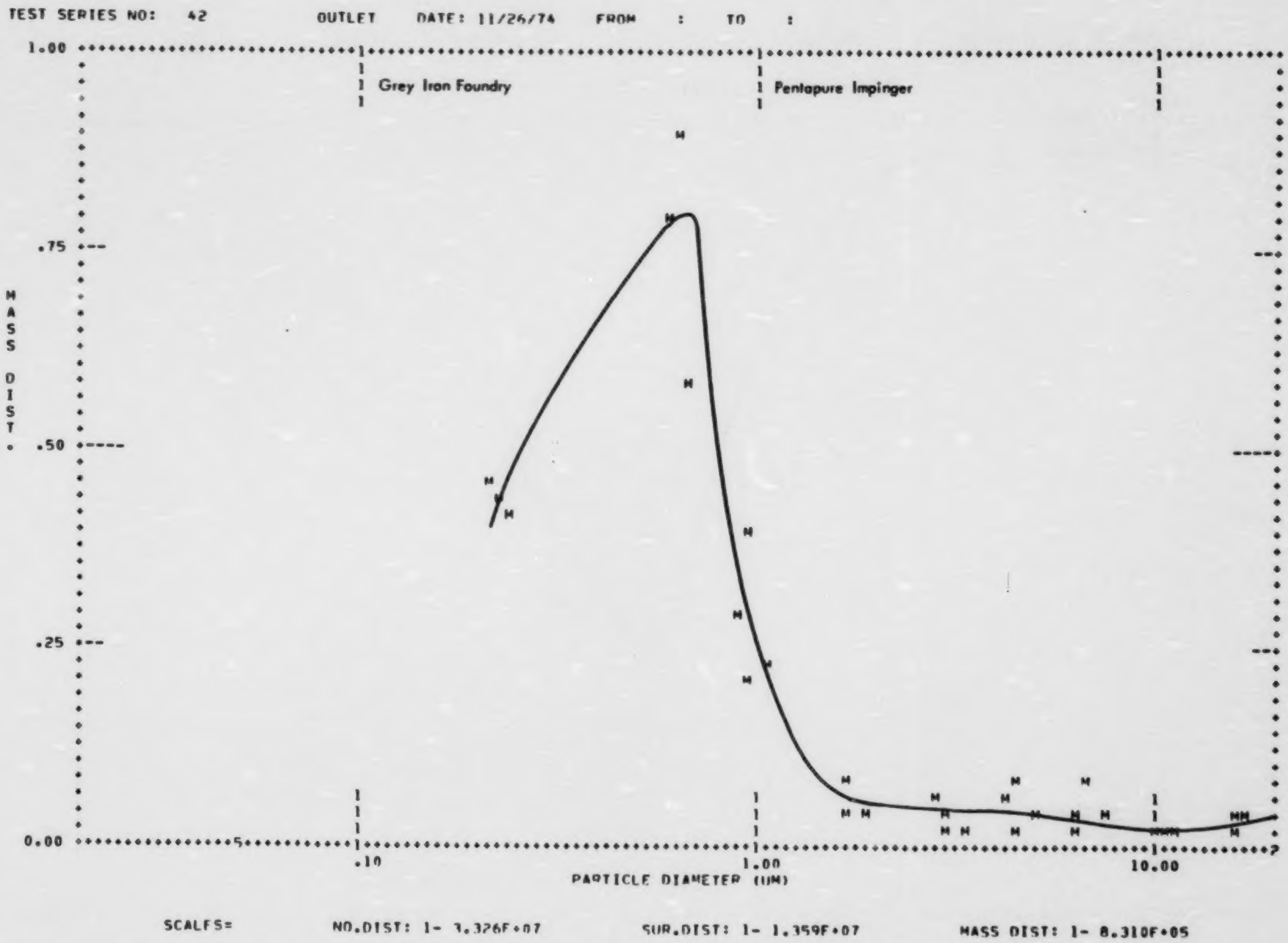


Figure A-75. Outlet Size Distributions of Test Series No. 42

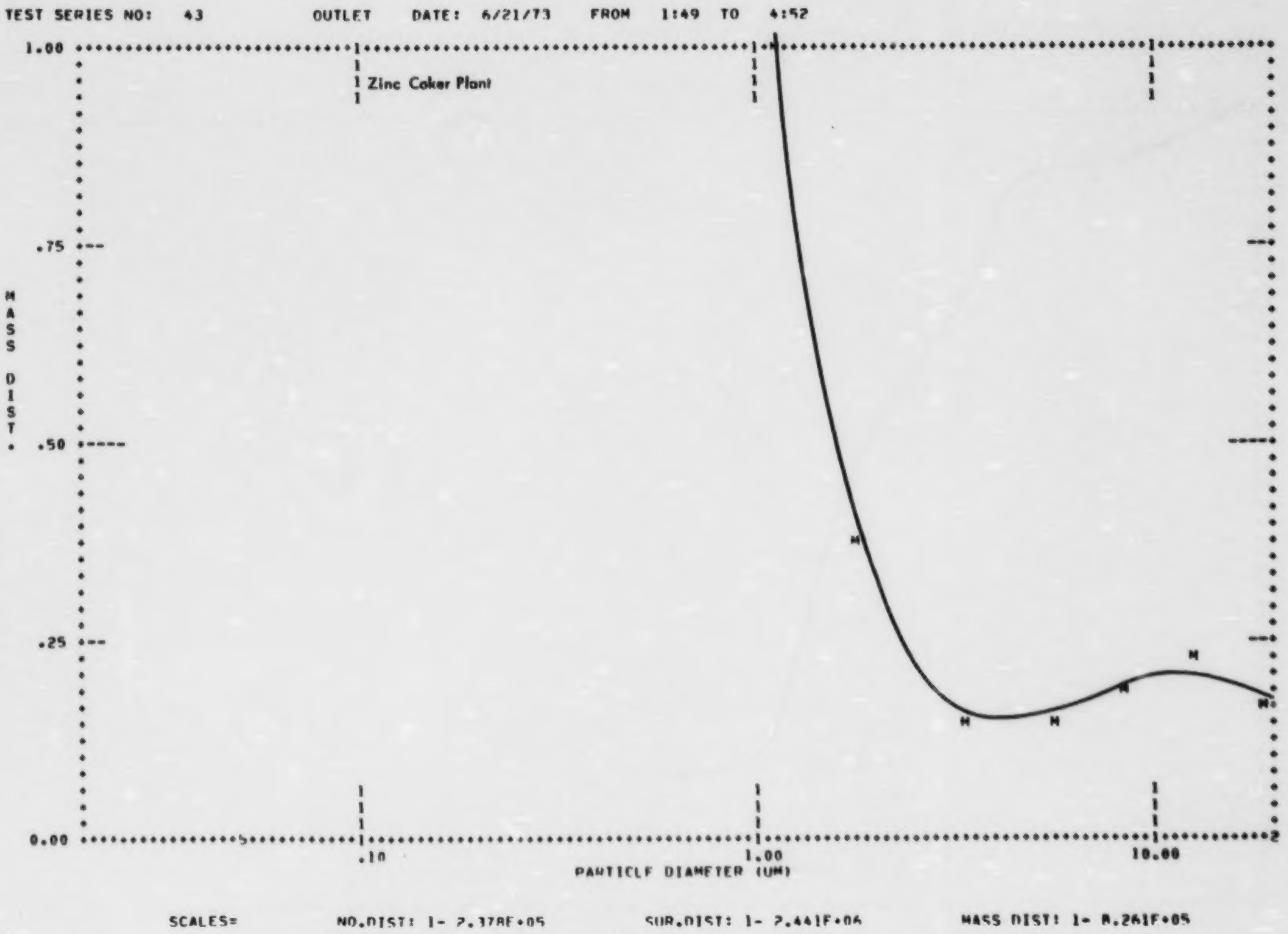


Figure A-76. Outlet Size Distributions of Test Series No. 43

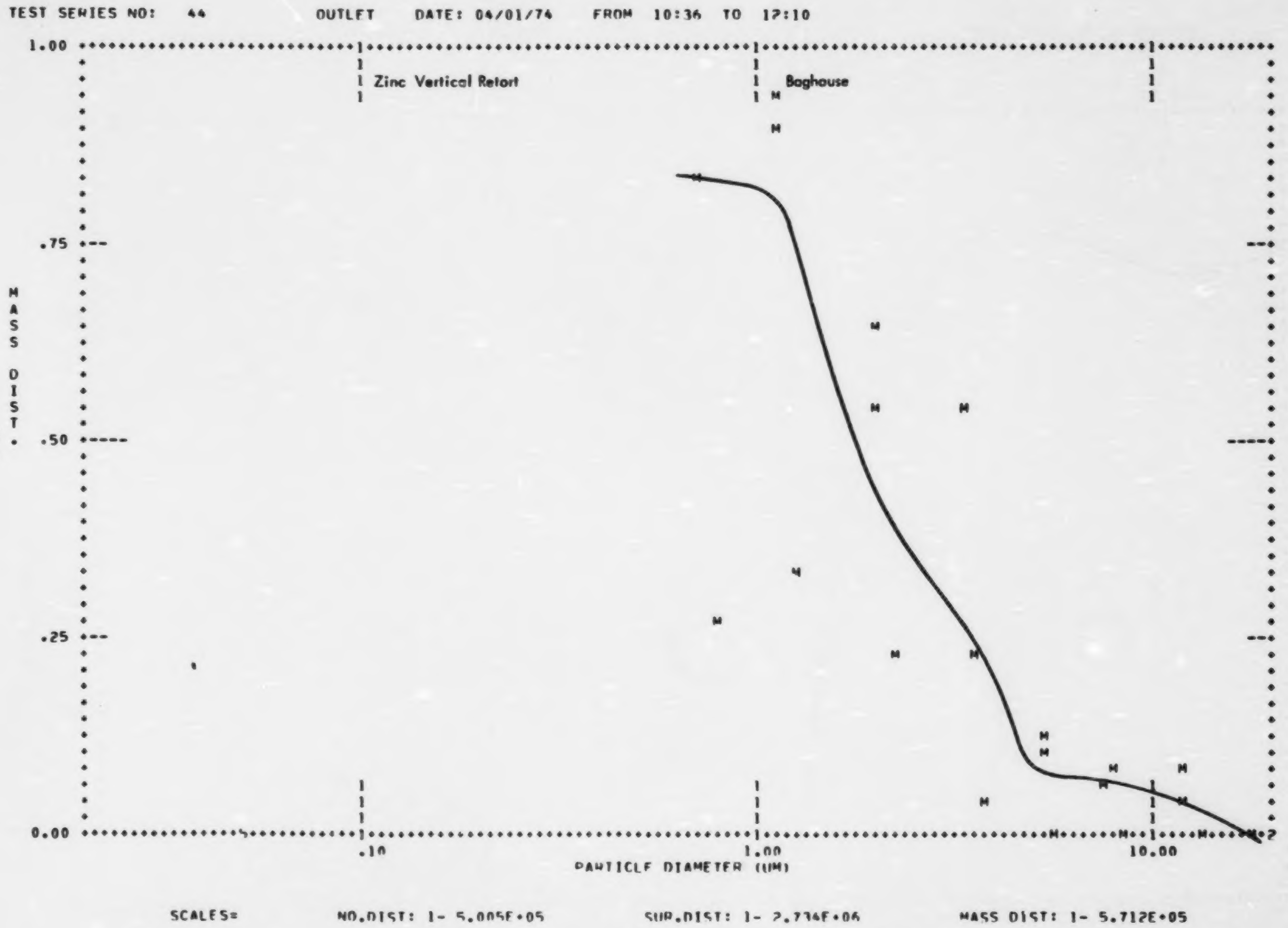


Figure A-77. Outlet Size Distributions of Test Series No. 44

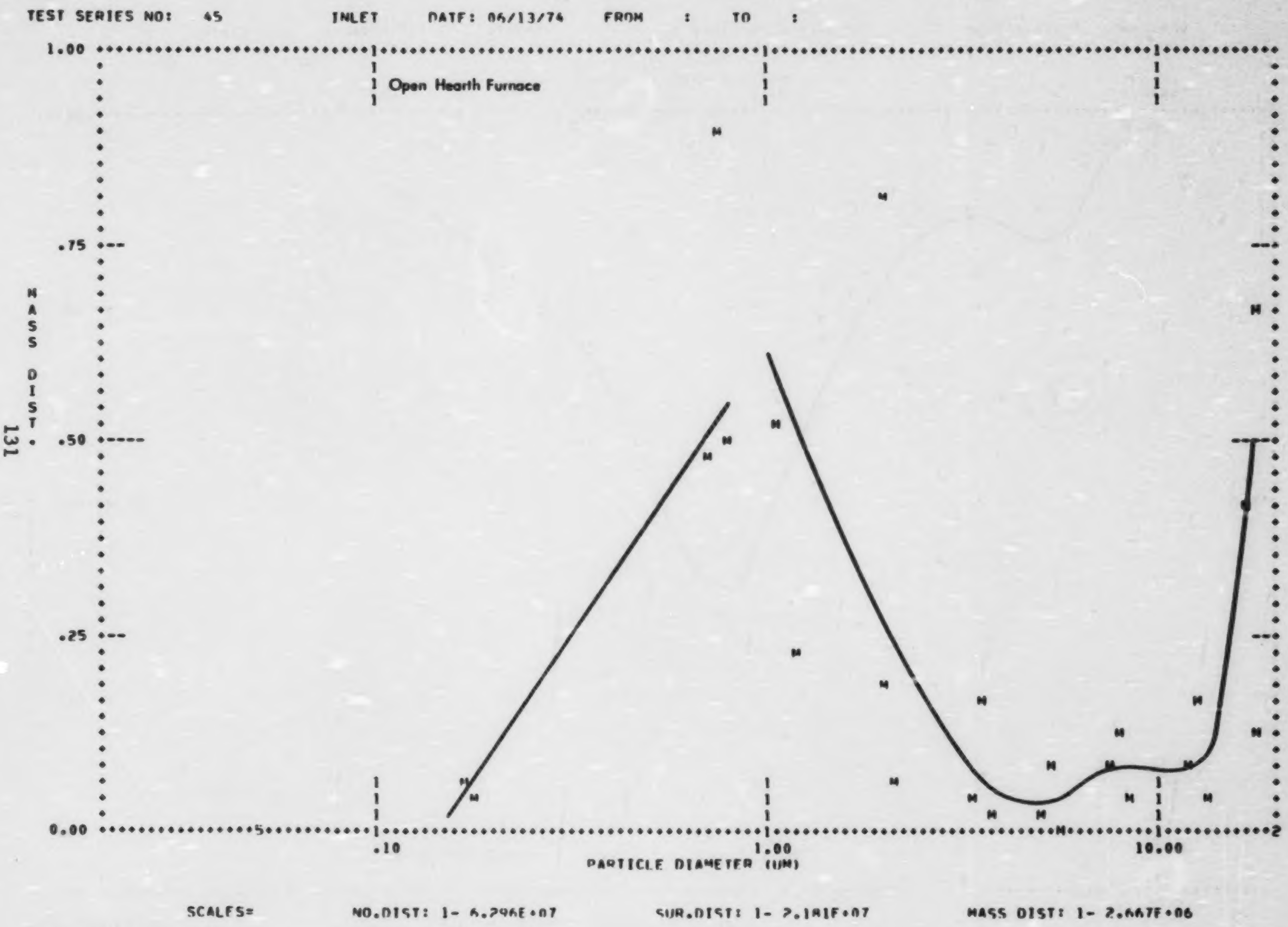


Figure A-78. Inlet Size Distributions of Test Series No. 45

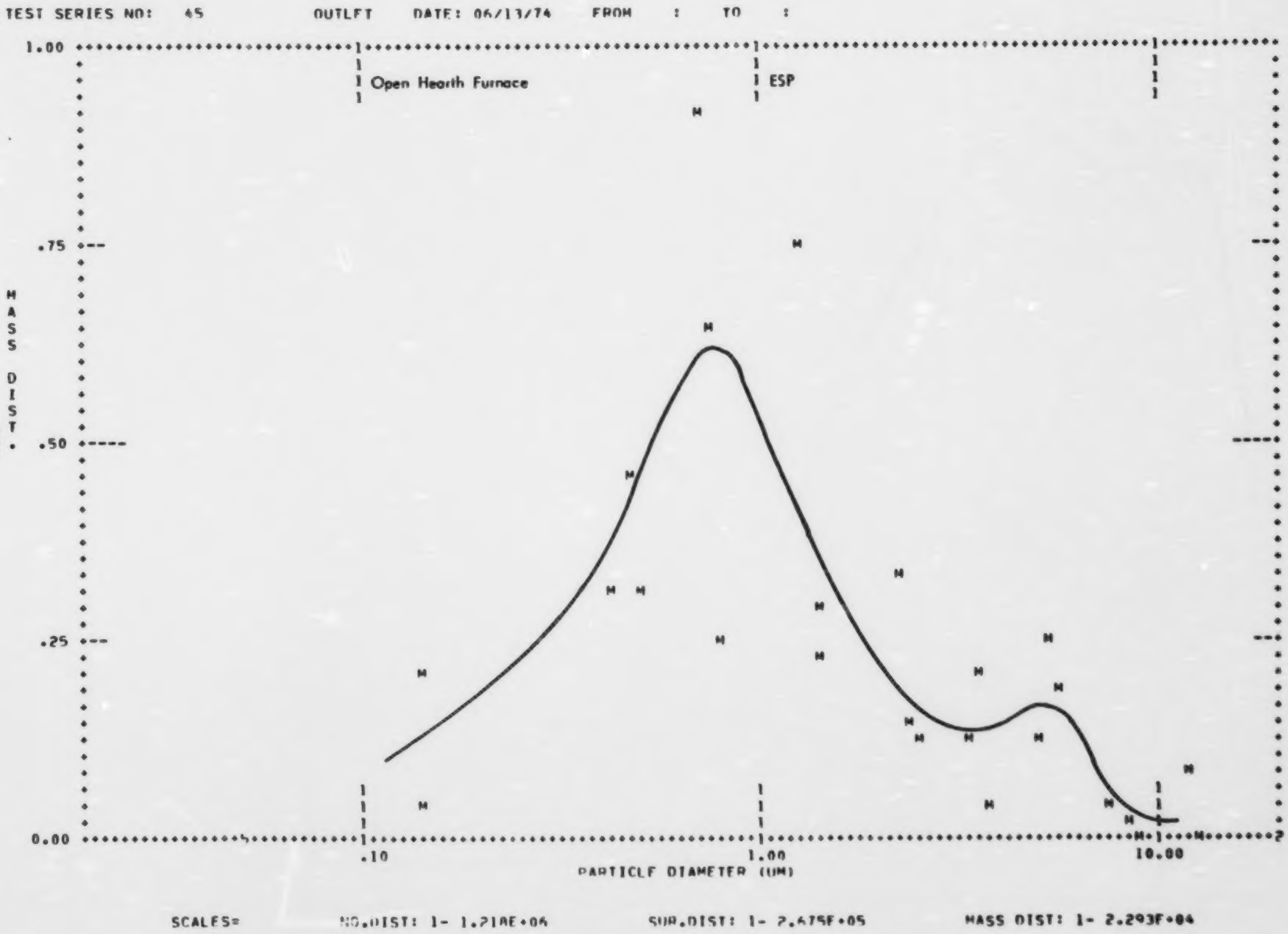


Figure A-79. Outlet Size Distributions of Test Series No. 45

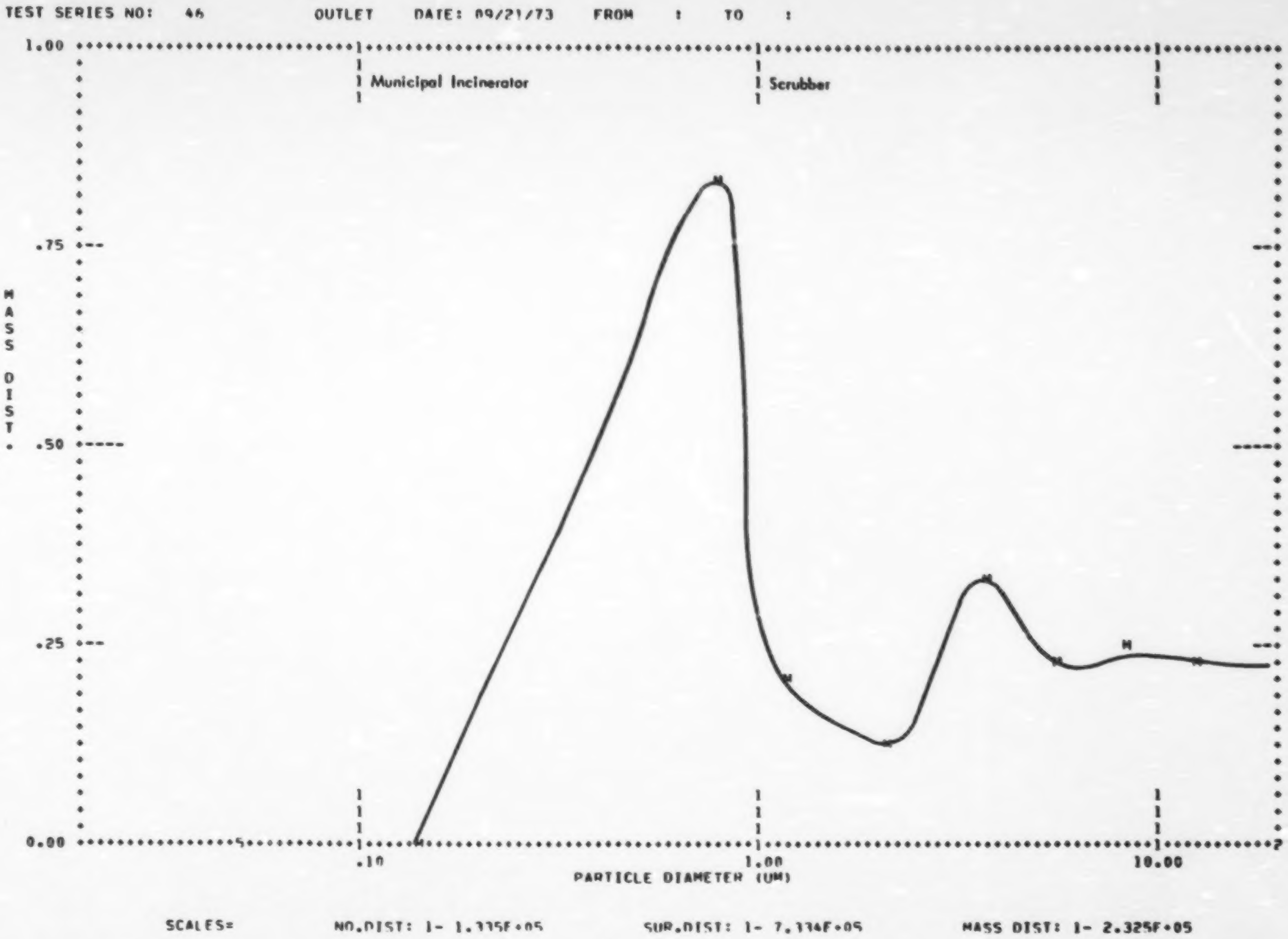


Figure A-80. Outlet Size Distributions of Test Series No. 46

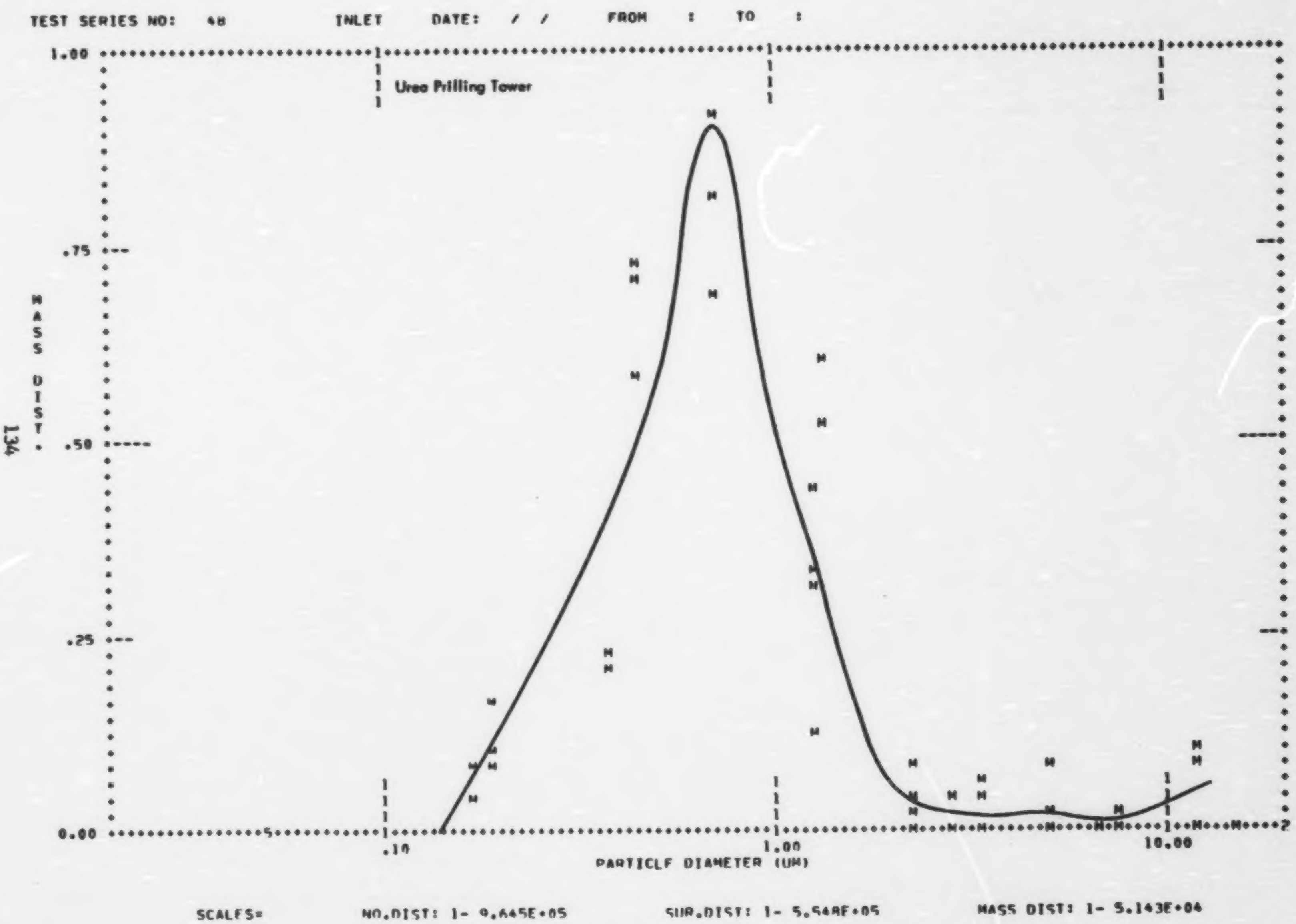


Figure A-81. Inlet Size Distributions of Test Series No. 48

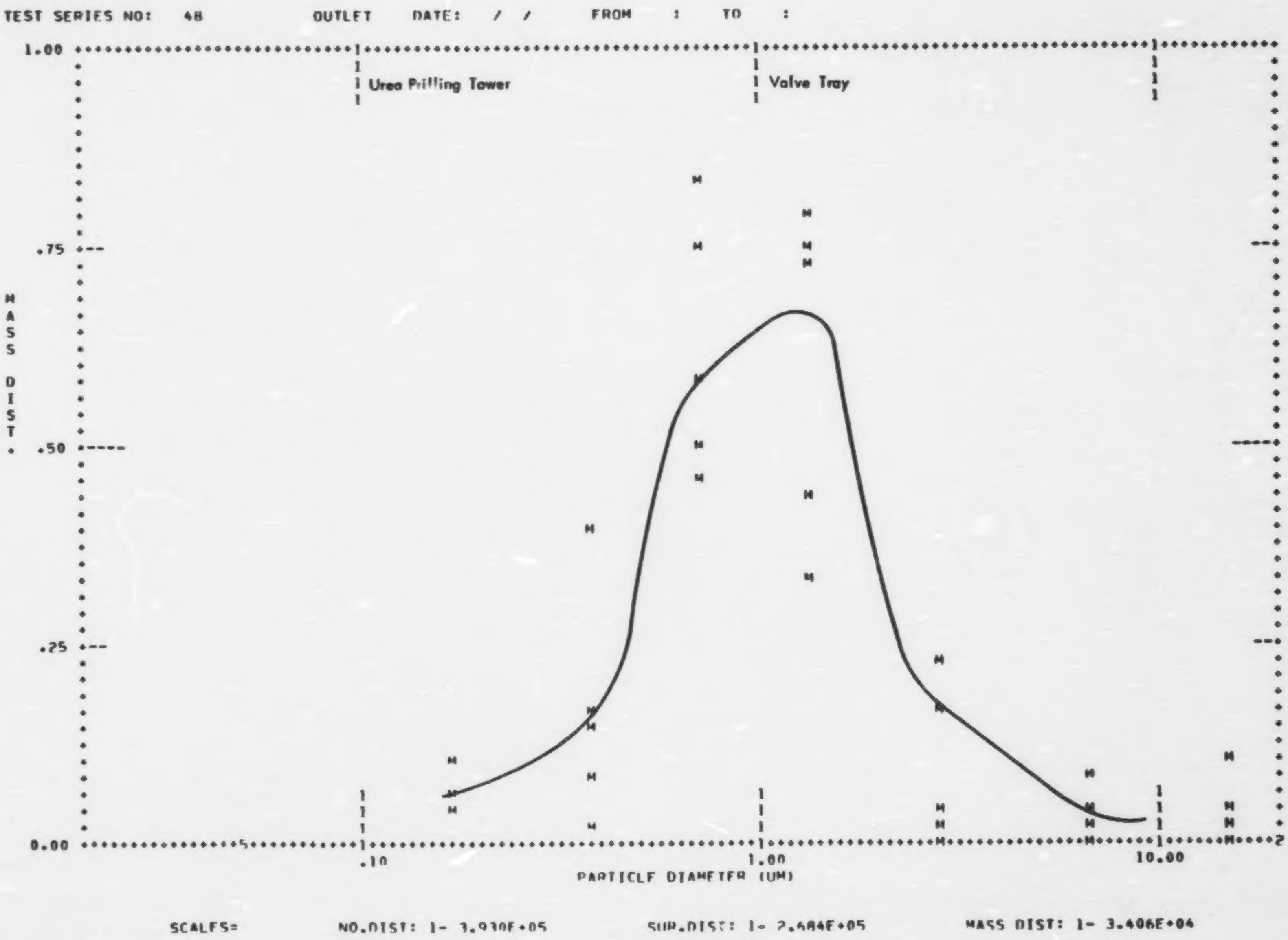


Figure A-82. Outlet Size Distributions of Test Series No. 48

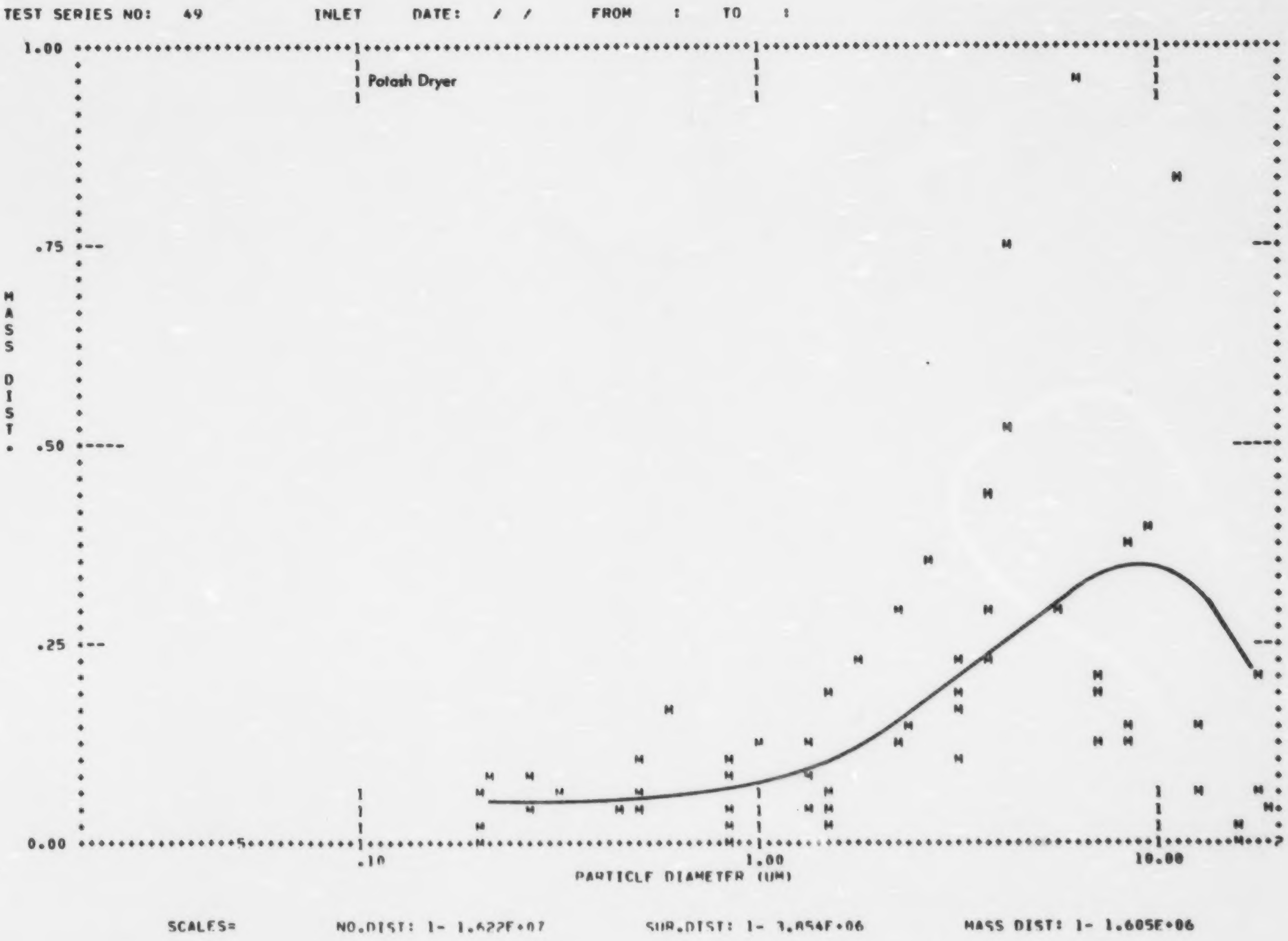


Figure A-83. Inlet Size Distributions of Test Series No. 49

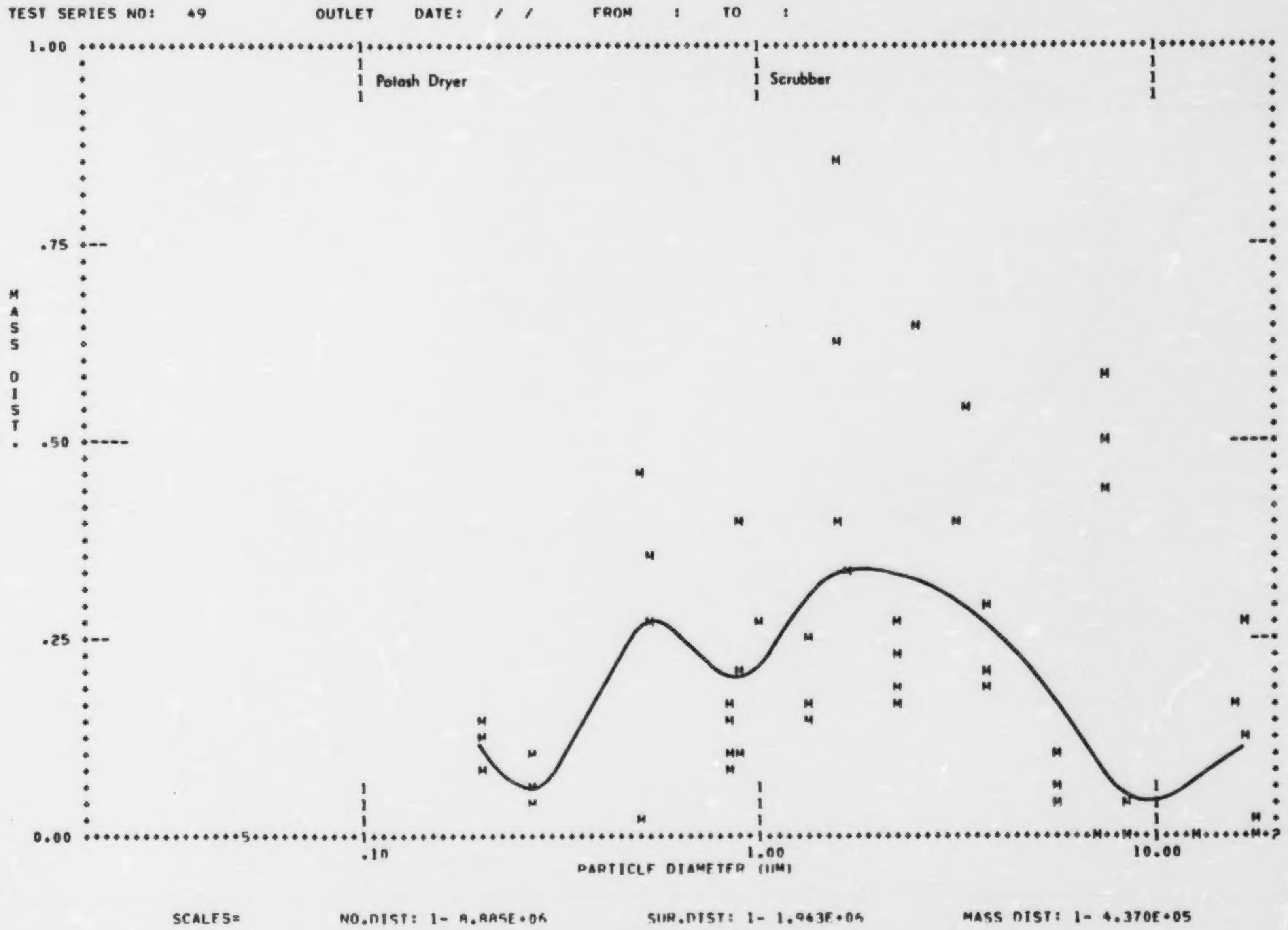


Figure A-84. Outlet Size Distributions of Test Series No. 49

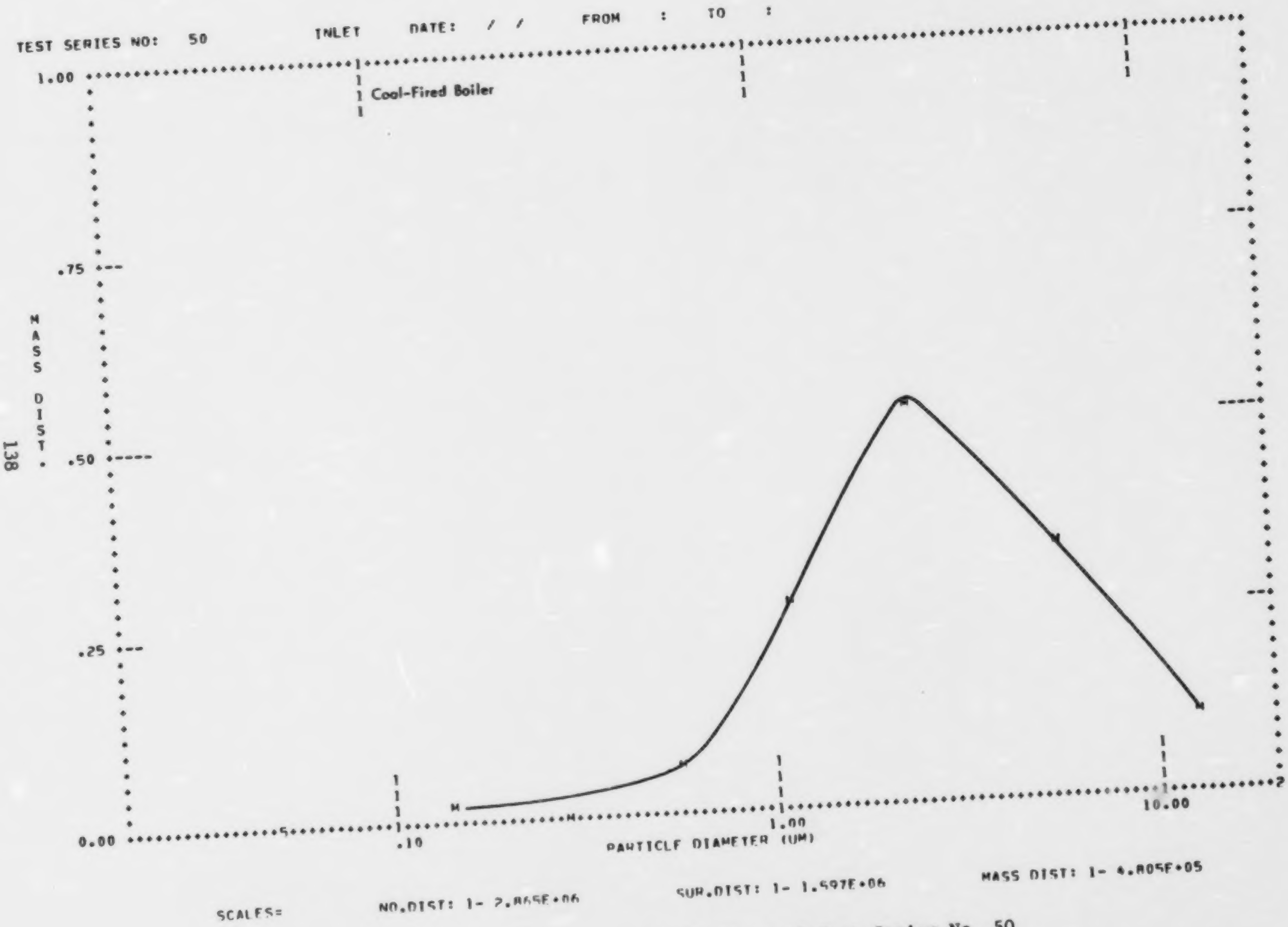


Figure A-85. Inlet Size Distributions of Test Series No. 50

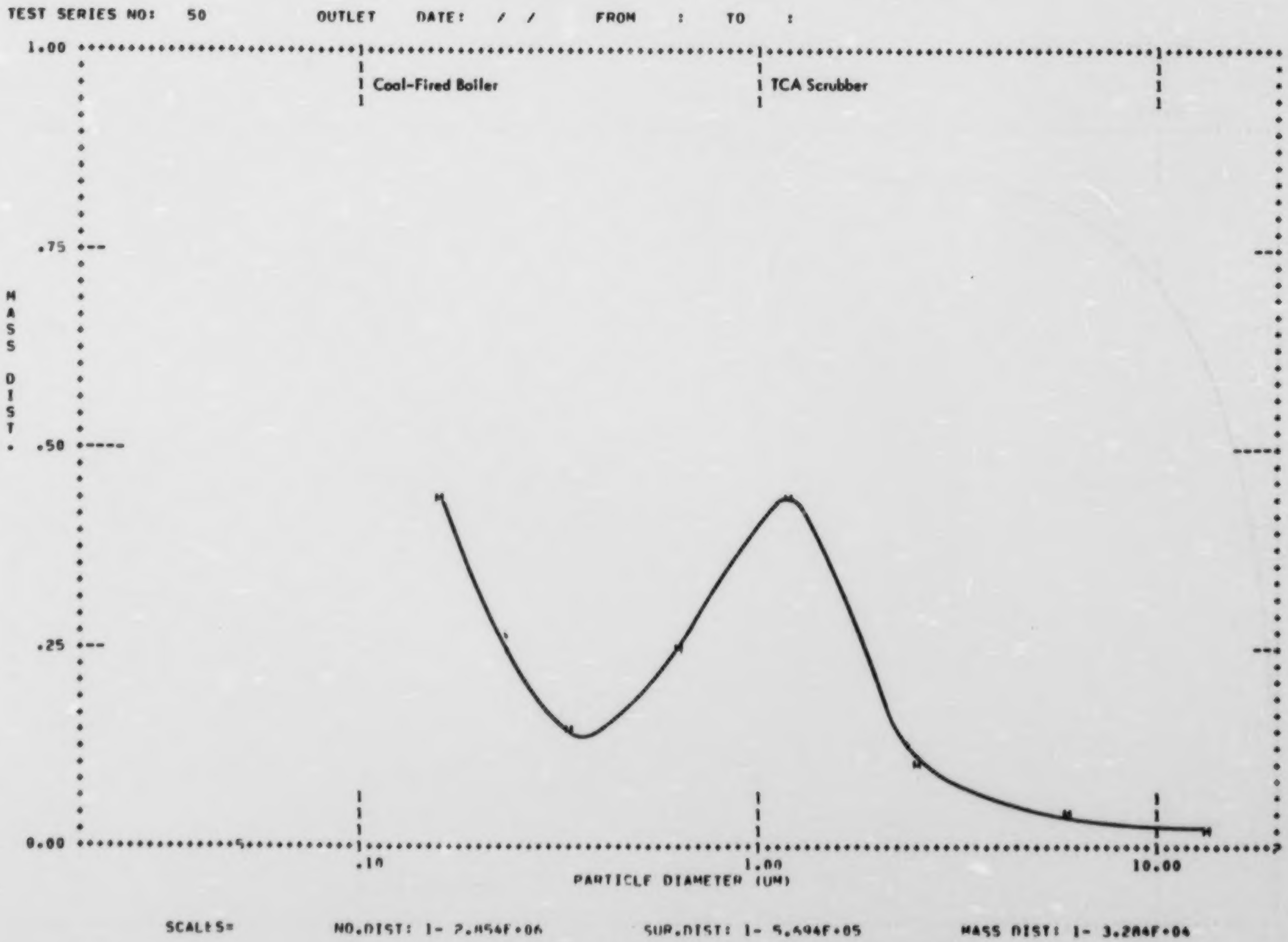


Figure A-86. Outlet Size Distributions of Test Series No. 50

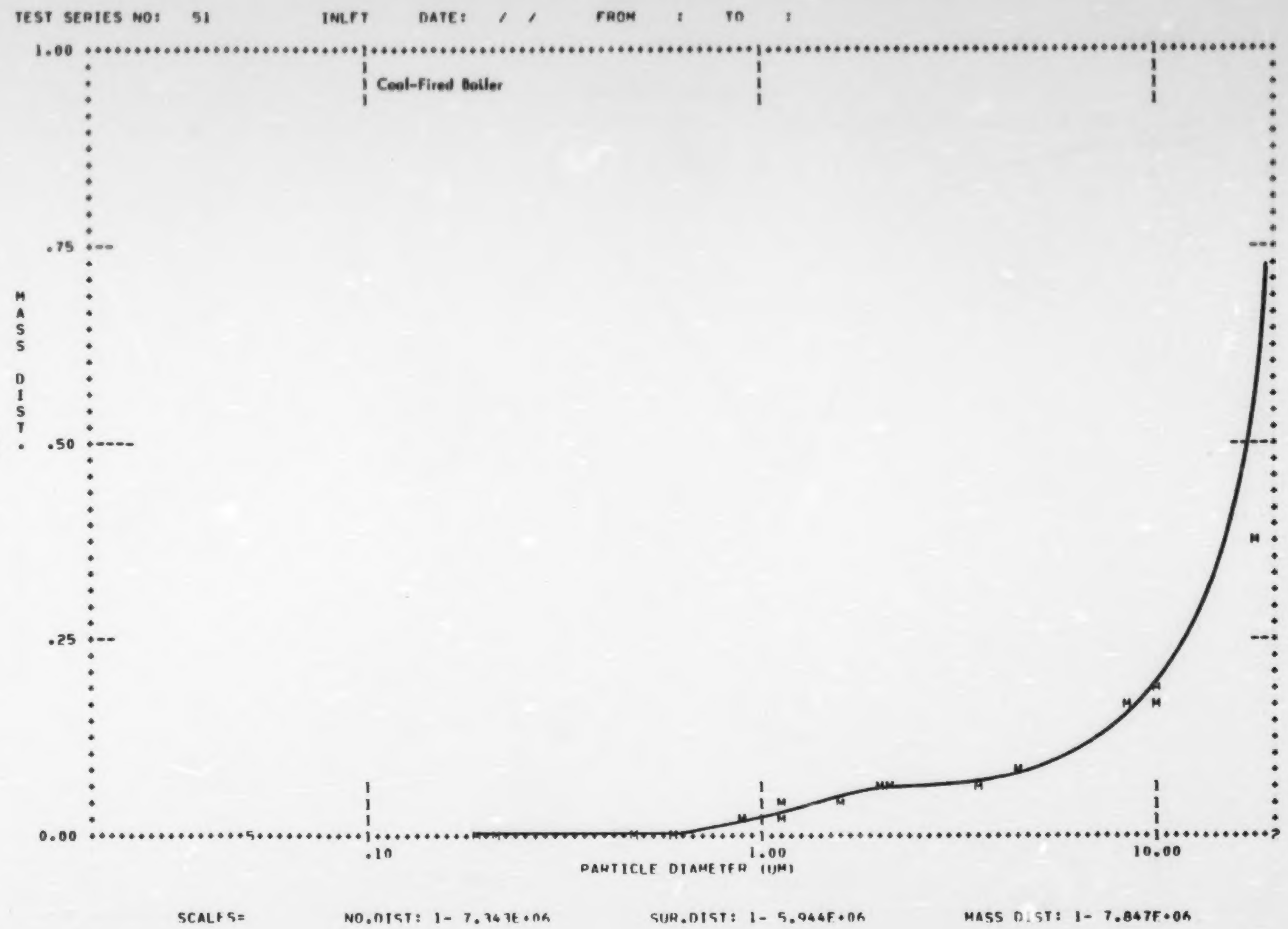
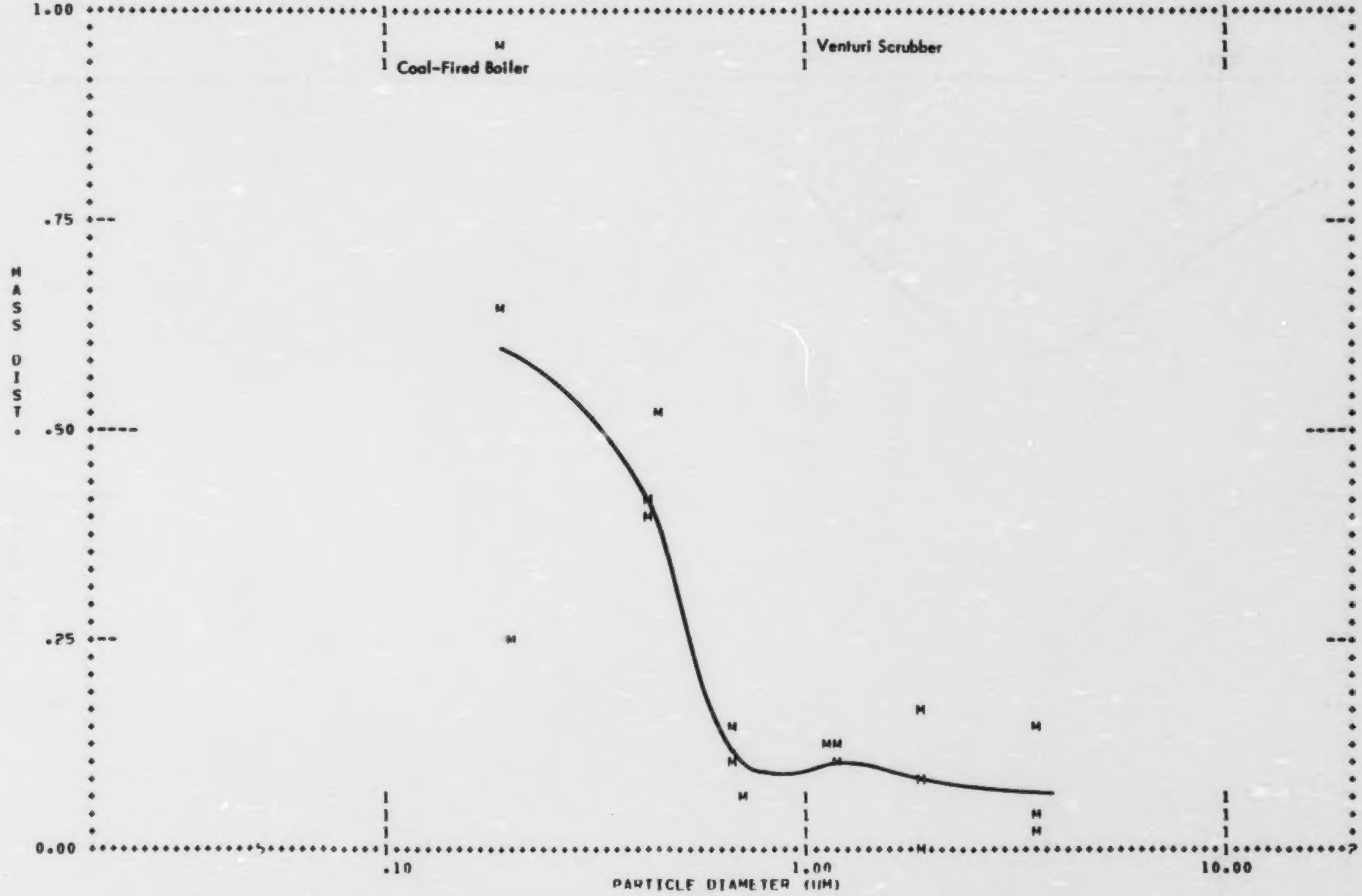


Figure A-87. Inlet Size Distributions of Test Series No. 51

TEST SERIES NO: 51 OUTLET DATE: / / FROM : TO :



SCALES= NO.DIST: 1- 2.066E+07 SUR.DIST: 1- 5.185E+06 MASS DIST: 1- 2.116E+05

Figure A-88. Outlet Size Distributions of Test Series No. 51

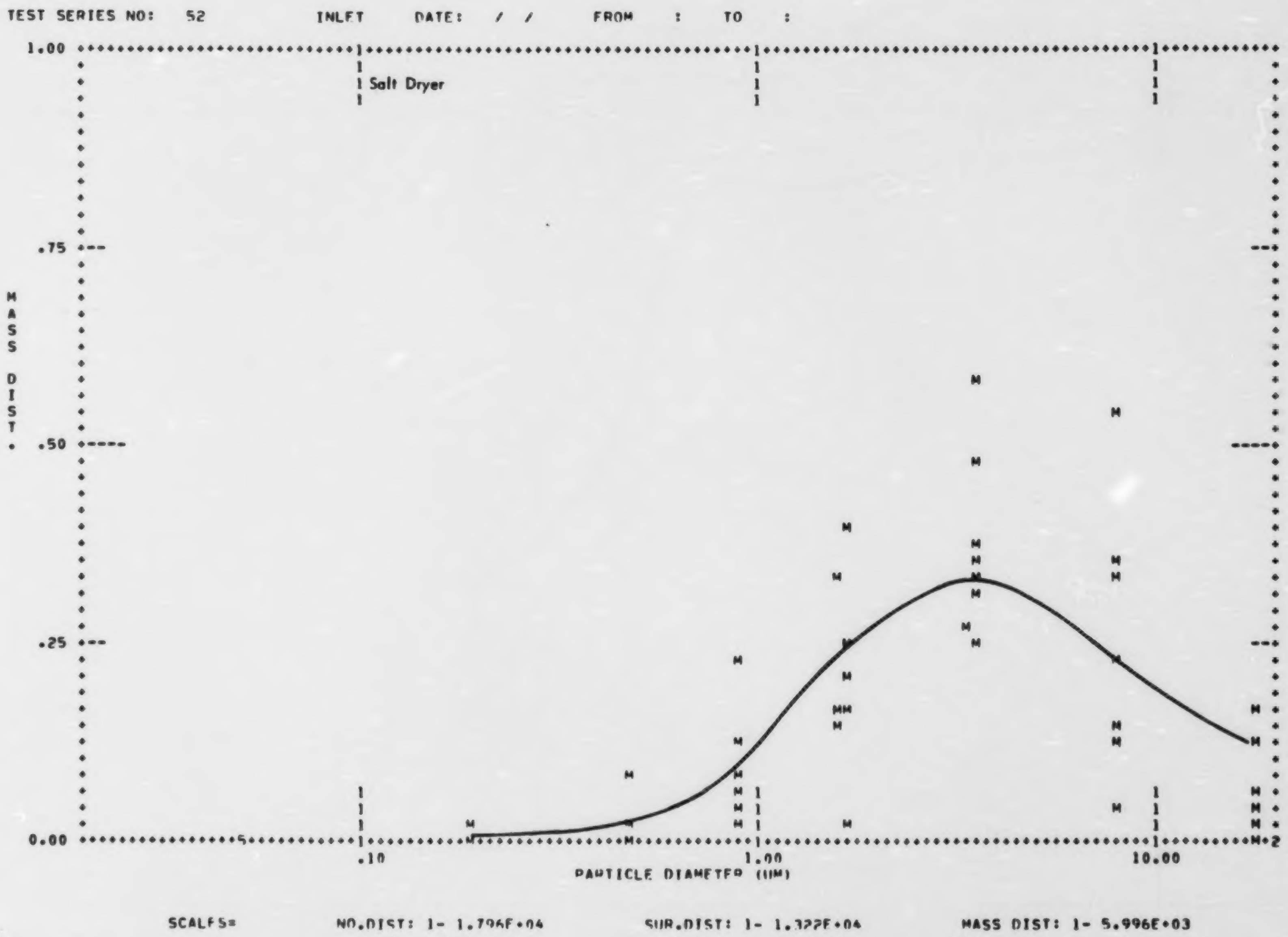


Figure A-89. Inlet Size Distributions of Test Series No. 52

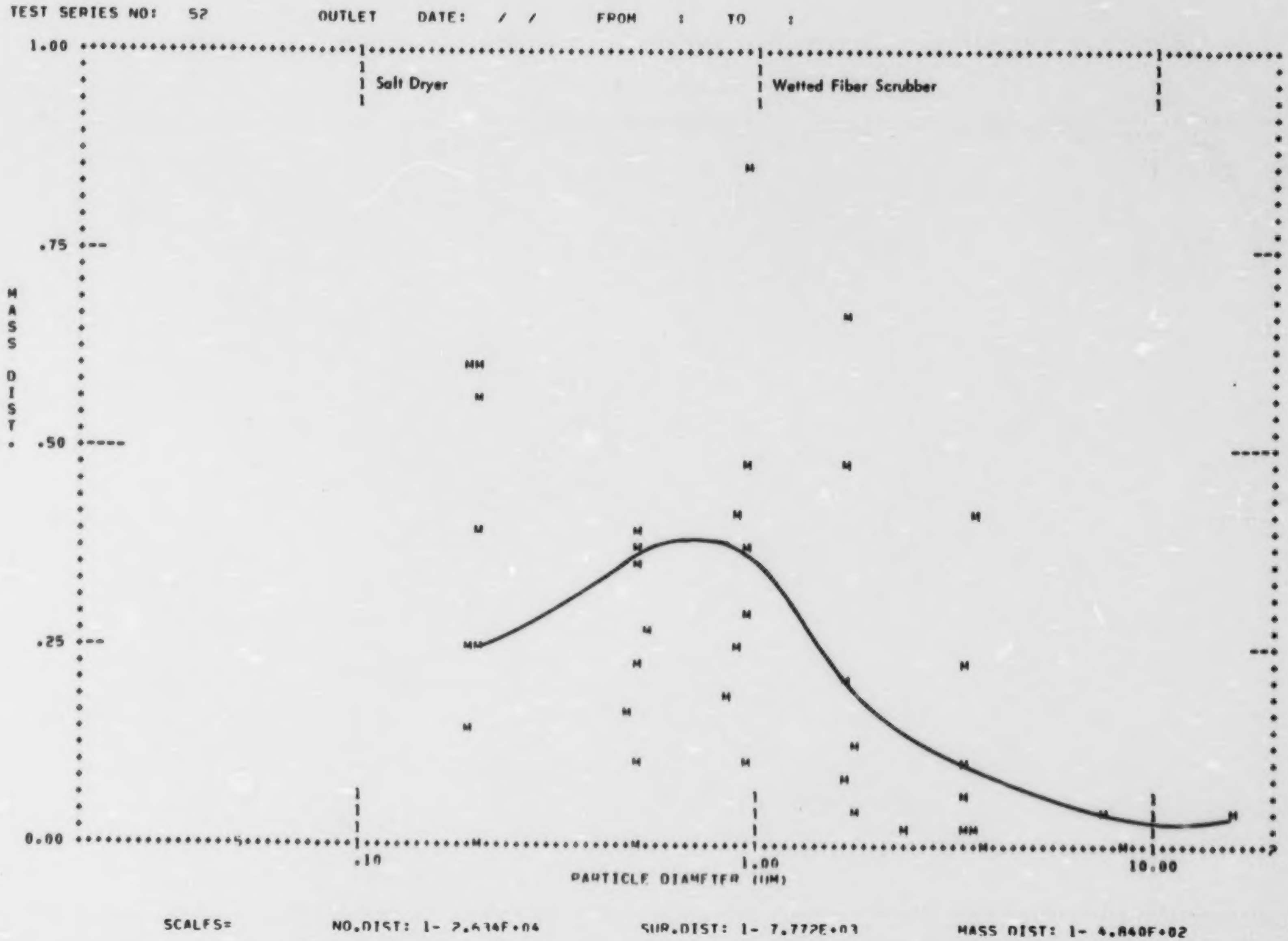


Figure A-90. Outlet Size Distributions of Test Series No. 52

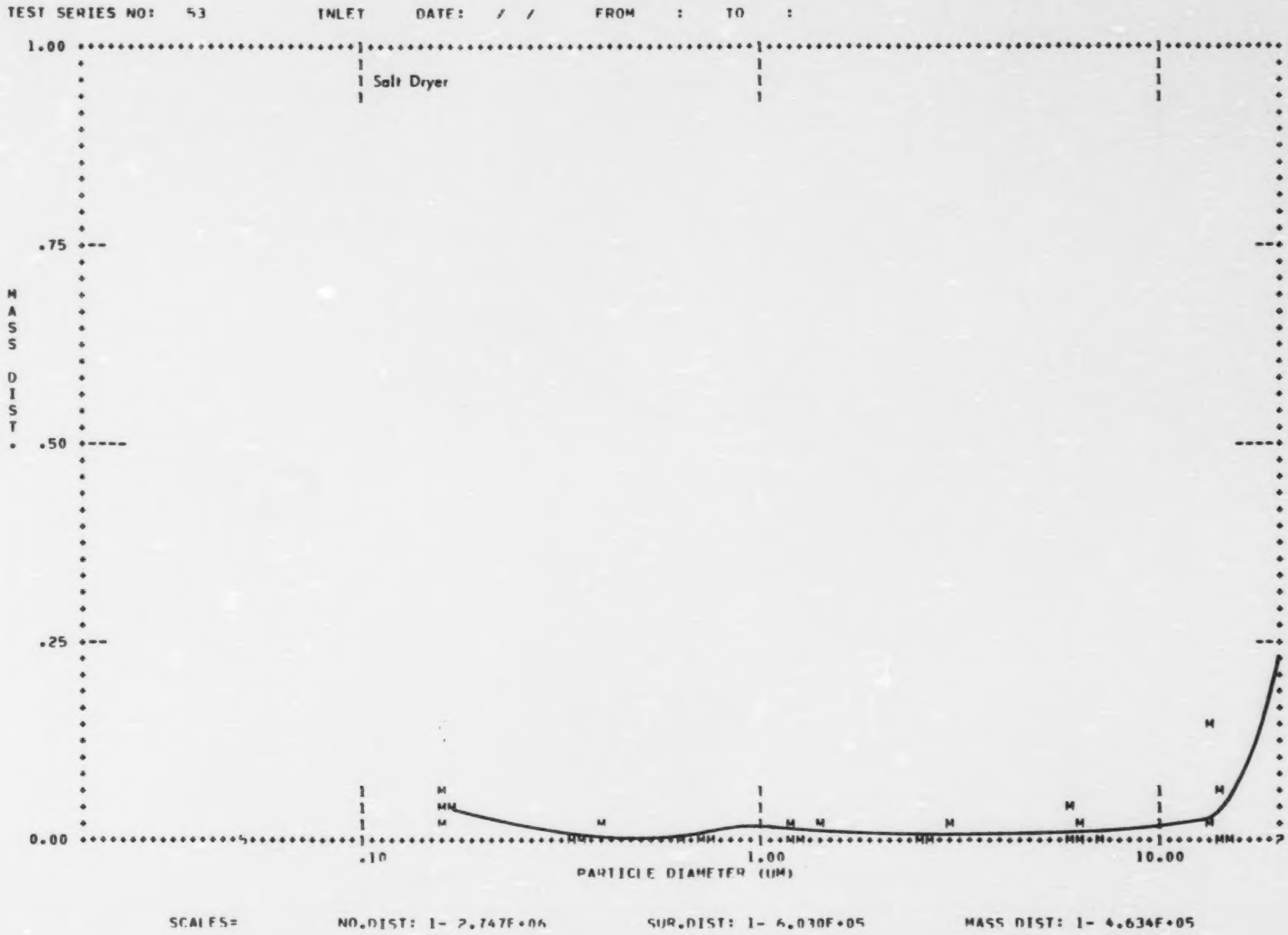


Figure A-91. Inlet Size Distributions of Test Series No. 53

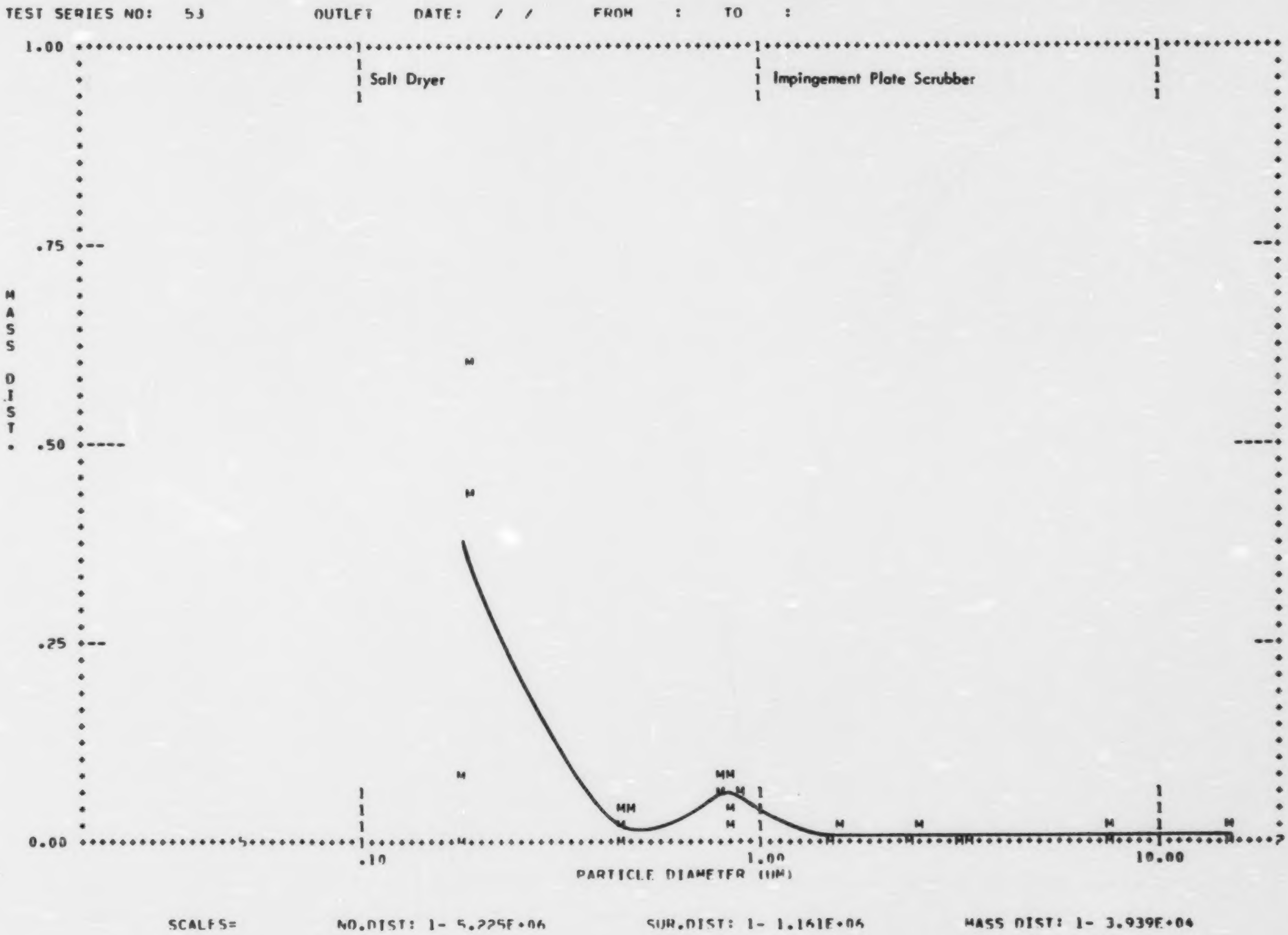


Figure A-92. Outlet Size Distributions of Test Series No. 53

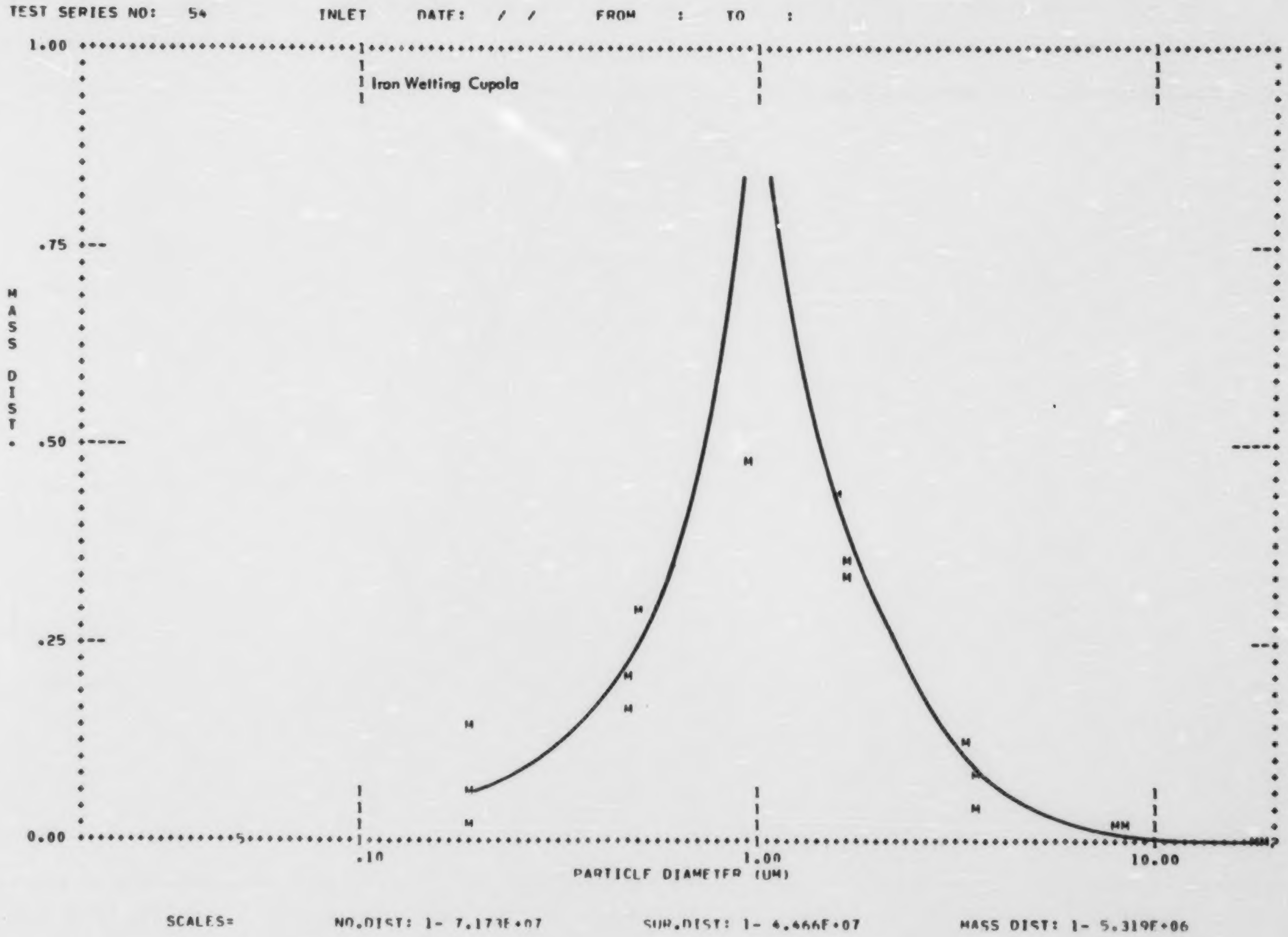


Figure A-93. Inlet Size Distributions of Test Series No. 54

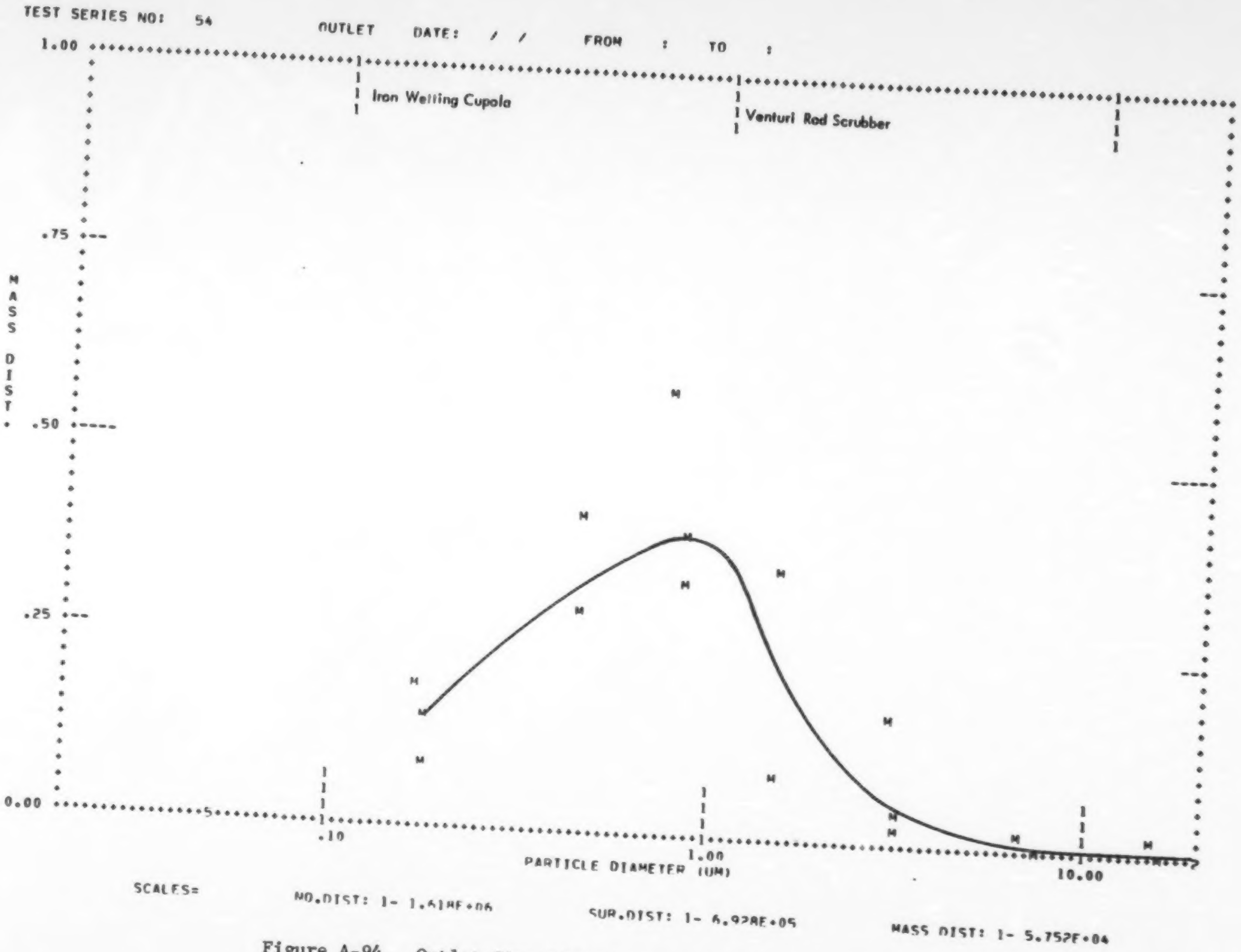


Figure A-94. Outlet Size Distributions of Test Series No. 54

APPENDIX B

PARTICULATE SAMPLING AND MEASUREMENT METHODS

INTRODUCTION

There are few particle size measuring devices suitable for stack sampling which are noncontact/nonextractive (transmissometers for instance). Most particulate size measurement instruments require that the aerosol be sampled and transported some distance (from the sampling point to the measurement location) before they are measured. What is required is a representative sample, i.e., a sample which is identical with the aerosol from which it was taken, with respect to the concentration, particle size distribution, chemical composition, etc. In the following sections the state of the art of aerosol sampling, aerosol transport, and aerosol measurement methods are reviewed briefly.

SAMPLING OF AEROSOLS

A representative and accurate sample of an aerosol will be obtained only if the sample air is withdrawn isokinetically. Under isokinetic sampling, the velocity (speed and direction) of the sampled air and hence the velocity (speed and direction) of the particulates approaching the sampler are undisturbed from their mainstream values. In practice it is very difficult to attain.

Because of the practical importance of accurate particle sampling, many workers have studied theoretically and empirically the errors arising from anisokinetic sampling. A recent paper by Fuchs (1) reviews the state of the art.

When the Reynolds number for particles is less than one, the anisokinetic errors are a function of two parameters.

The anisokinetic parameter, $R = \overline{u}/U_o$,

The Stokes number, $K = \frac{V_s\ U_o}{d\ g}$

where U_o = stream velocity

$\overline{u}$ = mean suction velocity

V_s = particle sedimentation velocity

d = characteristic length of the system (for a sampling nozzle it is the I.D. of the nozzle)

g = acceleration of gravity.

The aspiration coefficient, A , is defined as:

$$A = C_i/C_o$$

where C_i = aerosol concentration in the sample

C_0 = aerosol concentration in the mainstream

When the sampling probe is parallel to the flow stream lines (i.e., conditions of isoaxiallity are met) and when $R = \overline{u}/U_0 < 1$ the flow lines diverge at the entry into the probe, the particles drift under the action of inertia across the flow lines toward the axis and as a result, the concentration in the sample becomes larger than in the duct ($A > 1$). At $R > 1$, everything is reversed and $A < 1$.

For probes with very thin (0.1 mm) walls, the aspiration coefficient can be approximated by an empirical formula (2) applicable in the range of $0.2 < R < 5$.

$$A = 1 + \left(\frac{1 - R}{R}\right)\left[\frac{(2 + 0.62\ R)\ k}{1 + (2 + 0.62\ R)k}\right] \qquad \text{(B-1)}$$

There are no reliable data available to assess the error caused by non-isoaxial sampling. However, from elementary considerations, it can be shown that at small θ values

$$A \approx 1 - 4 \sin \theta \cdot K/\pi \qquad \text{(B-2)}$$

where θ is the angle between the flow directions in the duct and the sampling probe.

Since the aspiration coefficient depends on K, i.e., on the particle size, when $A \neq 1$, not only is the determination of the aerosol concentration erroneous, but the sample cannot be representative.

AEROSOL TRANSPORT

Here the question is, "When an aerosol is transported through a tube of certain diameter, length, and flow velocity, what fraction of the particles are deposited on the inner walls of the transport tube and what fraction penetrates the tube?" Usually the flow condition in transport tubes is turbulent. It is important to know particle penetration or loss as a function of particle size and other aerosol properties.

Particle loss in transport tubes may occur by the following mechanisms:

- Inertial impaction;
- Centrifugal separation;
- Turbulent deposition;
- Gravitational settling;
- Diffusive deposition;
- Condensation and coagulation growth;
- Thermophoretic effects; and
- Electrostatic effects.

In the case of large particles or high flow velocities, the first three mechanisms will be predominant. Gravitational settling will be significant for large particles and low flow velocities, i.e., for $V_{settling}/V_o > 1$. Diffusive deposition will be a significant mechanism for particles smaller than 0.1 μm. Thermophoretic, electrostatic, and condensation and coagulation growth depend upon the state of the aerosol and electrical charge on the particles. Good discussions of these mechanisms can be found in Refs. 3, 4, and 5.

AEROSOL MEASUREMENT

Stationary point sources emit particles over a broader size range, from about 0.001 to over 100 μm. All portions of the size range are important in defining the pollutant potential of particulate emissions.

Physical laws governing particle behavior are different for different sized particles and no single instrument/principle is applicable to the entire size range. For this reason, numerous types of instruments are used, each applicable to a limited size range, and each based on one or two of several physical principles.

Table B-1 shows the general class of instruments and their applicable size ranges. These instruments are described briefly in the following sections.

INERTIAL IMPACTORS

Because of their simplicity, compactness, ruggedness, and ease of operation, impactors are the most widely used instruments for measuring particle size distributions in flue gases.

TABLE B-1. PARTICLE SIZE MEASUREMENT INSTRUMENT TYPES

Technique	Instrument type	Size range (μm)
Inertial	Cascade impactors	0.3-30*
	Cyclone samplers	0.5-30
Optical	Single particle light scattering counters	0.3-30
	Nephelometers	0.1-10
	Transmissometers	0.1-10
Diffusional	Diffusion battery/condensation nuclei counters	0.005-0.1
Electrical	Electrical aerosol analyzers	0.005-1
Other	Sedimentation and elutriation	1-100
	Centrifugal separators	2-100
	Electrical conductivity	0.5-100
	Optical microscopy	0.5-100
	Electron microscopy	0.002-10

* Low pressure cascade impactors may prove useful down to 0.05 μm for some applications where volatile particles are not present.

All impactors operate under the principle that if a stream of particle-laden air is directed at a surface, particles of sufficient inertia will impact upon the surface and smaller particles will follow the air streamlines and not be collected. Thus, an impactor consists simply of a nozzle, either round or rectangular in shape, and an impaction plate.

A cascade impactor consists of several impactor stages in series in which the aerosol stream is passed from stage to stage with continually increasing velocities and decreasing particle cut-off sizes. The particle size distributions are calculated from the mass collected on various stages and the cut-off sizes of the stages. Some of the cascade impactors commercially available are listed in Figure B-1.

To obtain reliable data from an impactor, one must be aware of their limitations. For example, theoretical prediction of impactor performance is accurate only when the design and operation of the impactor follows the theoretical model. It is essential to calibrate the impactors experimentally. Other nonideal characteristics of impactors one must be aware of are wall loss, particle bounce, particle reentrainment, de-agglomeration or breakup, electrostatic effects, nonideal collection surfaces, and condensation or reaction of gases with the particulate or substrate.

The nonideal collection characteristics of inertial impactors were studied recently (6-7) and tentative procedures exist for particle sizing in process streams using cascade impactors (8).

VIRTUAL IMPACTOR

A virtual impactor (9) uses the principle of inertial separation, but impaction plate is replaced by a region of relatively stagnant air (Figure B-2).

The virtual surface formed by the deflected streamlines realizes similar boundary conditions to those in real impactors. Large particles will pass into the forward low-flow region while small particles will remain mostly in the high-flow air stream deflected radially around the receiving tube. Both size fractions can subsequently be deposited onto separate filters.

CYCLONE SAMPLERS

Cyclones have been used less than impactors for making particle size distribution measurements because they are bulky and give less resolution. However, in applications where larger samples are required, or where sampling times with impactors may be undesirably short, cyclones are better suited for testing than impactors. Cyclones are also frequently used as precollectors in impactor systems to remove large particles which might overload the upper stages.

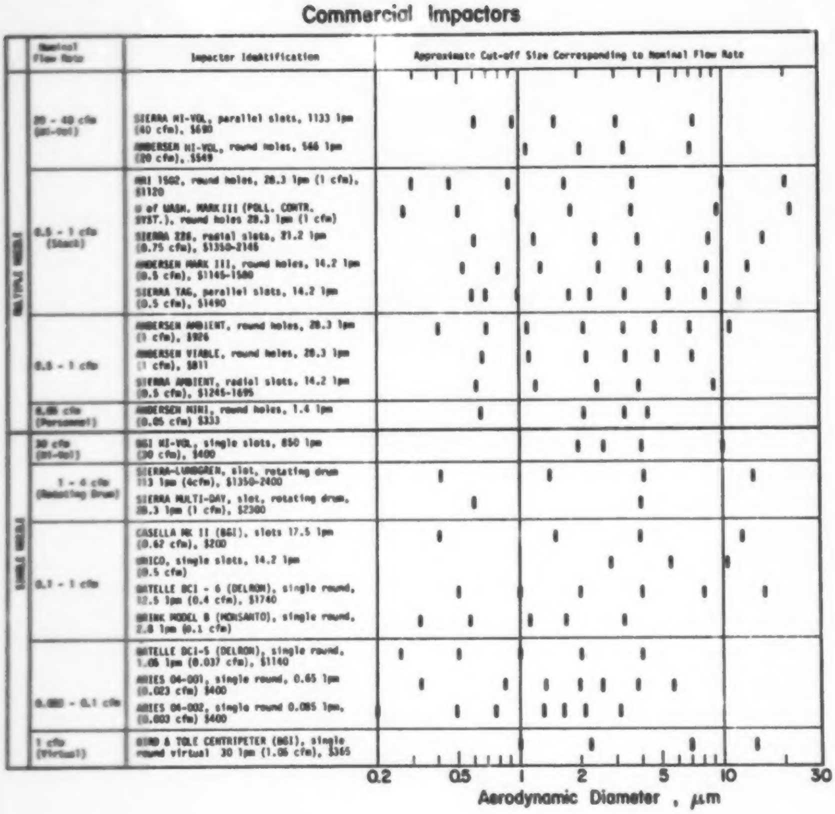


Figure B-1. Some Commercially Available Cascade Impactors

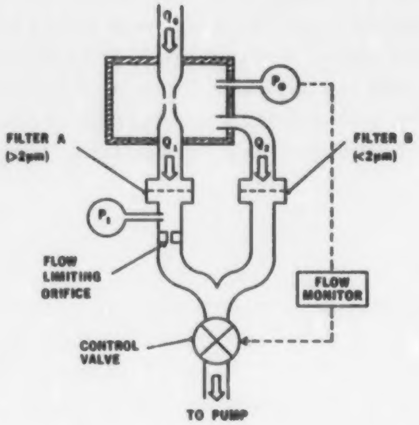

Q_0
P_0
FILTER A (>2μm)
Q_1
Q_2
FILTER B (<2μm)
P_1
FLOW LIMITING ORIFICE
FLOW MONITOR
CONTROL VALVE
TO PUMP

Figure B-2. Schematic Diagram of Virtual Impactor

Chang (10) developed a system of parallel cyclones which separates particles into four size fractions. This system is too large for in-stream sampling and thus employs a probe for sample extraction. Although the system is impractical for stack sampling, the discussions of cyclone design and calibration included in Chang's report are a good starting point for the design of small cyclones. Figure B-3 shows a schematic of a much simpler series cyclone system which was described by Rusanov (11) and is used in the USSR for obtaining particle size information. This device is operated in-stack, but because of the rather large dimensions requires a 20.3 cm port for entry. Smith et al. (7) have developed and tested a series cyclone system which is designed to operate at a flow rate of 28.3 liters/min and which is compact enough to fit through a 15.2 cm port. Complete calibration and preliminary performance testing of this system have been done. Series cyclone systems have adequate resolution for many purposes and should be much less susceptible to operator error than impactors and free from gas-substrate interferences. The main advantage of such systems, however, is the ability to collect large-sized samples for subsequent analysis.

OPTICAL PARTICLE COUNTERS

The basic operating principle for optical particle counters is illustrated in Figure B-4. Light is scattered by individual particles as they pass through a small viewing volume, the intensity of the scattered light being measured by a photomultiplier tube. The amplitude of the scattered light pulses determines the particle size and the rate at which the pulses occur is related to the particle concentration. Thus, a counter of this type gives both size and number information. The occurrence of more than one particle in the vewing volume is interpreted by the counter as a larger single particle. To avoid this effect, dilution to about 300 particles/cm^3 is necessary. The intensity of the scattered light depends upon the viewing angle, particle index of refraction, particle optical absorptivity, and shape, in addition to the particle size. The schematic in Figure B-4 shows a system which utilizes "near forward" scattering. Different viewing angles might be chosen to optimize some aspect of the counter performance. For example, near forward scattering minimizes the effect of variations in the indicated particle size with index of refraction, but for this geometry, there is a severe loss of resolution for particle sizes near 1 μm. Right angle, or 90 degrees scattering smooths out the response curve, but the intensity is more dependent on the particle index of refraction. Available geometries are:

Bausch and Lomb 40-1	Near Forward Scattering
Royco 220	Right Angle
Royco 245, 225	Near Forward
Climet CI-201	Integrated Near Forward

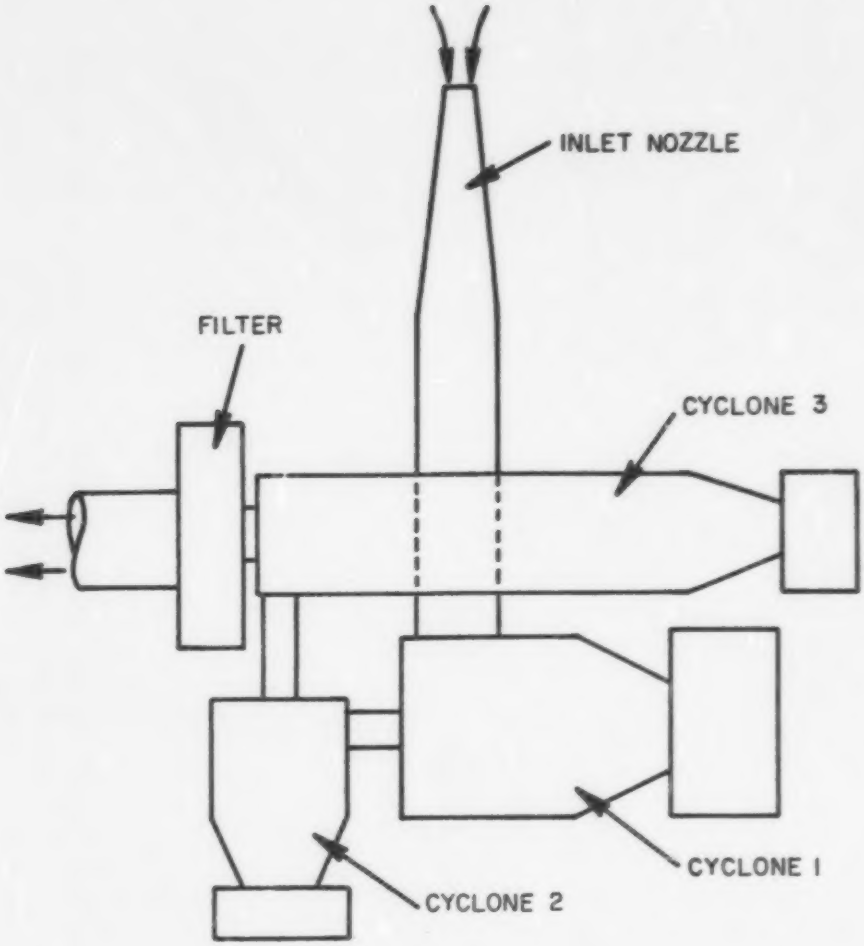

INLET NOZZLE
FILTER
CYCLONE 3
CYCLONE 1
CYCLONE 2

Figure B-3. Series Cyclone Used in the USSR for Sizing Flue Gas Aerosol Particles (11)

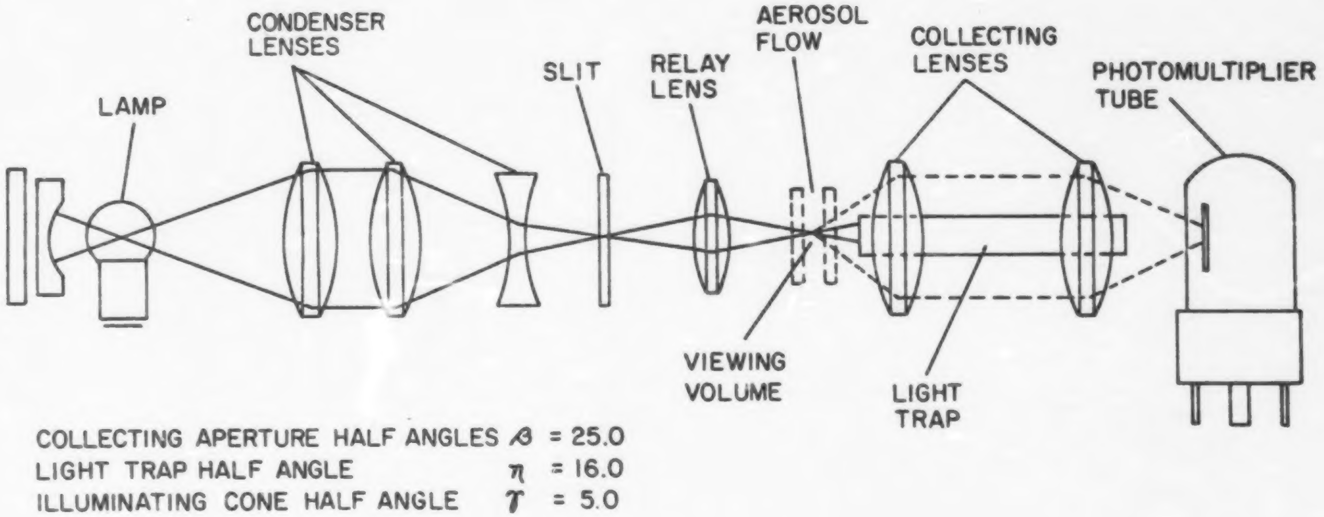

CONDENSER LENSES
LAMP
SLIT
RELAY LENS
AEROSOL FLOW
COLLECTING LENSES
PHOTOMULTIPLIER TUBE
VIEWING VOLUME
LIGHT TRAP
COLLECTING APERTURE HALF ANGLES β = 25.0
LIGHT TRAP HALF ANGLE η = 16.0
ILLUMINATING CONE HALF ANGLE τ = 5.0

Figure B-4. Schematic Diagram of the Optical System of the Royco PC 245 Optical Particle Counter (After Berglund)

LIGHT SCATTERING AND LIGHT ATTENUATION DEVICES

Aerosol photometers, not discussed here, measure light scattering or extinction from a cloud of particulates, and do not resolve the individual particle sizes. These measurements will provide accurate concentration measurements provided the size distributions remain the same.

DIFFUSION BATTERY/CONDENSATION NUCLEI COUNTER

The diffusion battery is an assembly of equally spaced parallel plates or a bundle of circular tubes of equal diamters or a series of screens. This device has long been used for the dynamic measurement of the size of aerosol particles in the diameter range 0.002 to 0.2 μm. Such particles are commonly called condensation nuclei, with the smaller sizes frequently called Aitken nuclei, after the inventor of the "dust counter." The larger sizes are called cloud condensation nuclei since they act to form cloud droplets at a supersaturation of 1% or less as occurs in the atmosphere.

The number concentration of condensation nuclei (CN) of all sizes is measured with CN counters which act to produce a supersaturation of about 300% by cooling the aerosol previously saturated with water vapor, usually by adiabatic expansion. The size is measured by passing the aerosol through several diffusion batteries of different lengths, or at different flow rates. The wide range of sizes has an even wider range of diffusion coefficients, varying from 10^{-2} cm^2/sec at 0.002 μm to 2×10^{-6} cm^2/sec at 0.2 μm. As a consequence, marked selective deposition according to size occurs by molecular diffusion. The size distribution may then be obtained by measurement of the concentration passing through a series of diffusion batteries.

A very compact lightweight diffusion battery made up of wire screens is described by Sinclair and Hoopes (12). This would be a valuable field instrument for stack sampling. The authors also provide a "graphical stripping" technique for calculating particle size distributions from raw data.

Diffusional measurements are less dependent upon the aerosol parameters than the other techniques discussed and perhaps are on a more theoretically firm basis.

Disadvantages of this technique are the bulk of the diffusional batteries, although advanced technology may alleviate this problem; the long time required to measure a size distribution; and problems with sample conditioning when condensible vapors are present.

ELECTRICAL AEROSOL ANALYZER

The electrical aerosol analyzer is a size distribution measuring instrument with in situ measurement capabilities over the 0.003 to 1 μm diameter range. The operating principle of the device is that of electrical charging and mobility analysis, a principle first described by Whitby and Clark (13).

Recent advances (Liu, Whitby, and Pui (14)) in charger and mobility design and the use of all solid-state electronics have resulted in an improved instrument that is portable (about 30 kg in weight) and considerably more versatile. Following is a brief description of this more recent device.

Figure B-5 is a schematic diagram of the instrument showing its major components: the aerosol charger, the mobility analyzer, the current sensor, and the associated electronic and flow controls. The instrument samples aerosols at the rate of 5 liters/min with an additional 45 liters/min of clean air needed to operate the mobility analyzer.

The EAA has the distinct advantage of very rapid data acquisition compared to diffusion batteries and condensation nuclei counters (2 min as opposed to 2 hr for a single size distribution analysis).

Disadvantages of this type of measurement system are: difficulties in predicting the particle charge, and the fraction of the particles bearing a charge, with sufficient accuracy; and the requirement for sample dilution when making particle size distribution measurements in flue gases.

OTHER SIZE ANALYSIS TECHNIQUES

Instruments included in this category are those which require particle collection and possibly redispersion.

Laboratory Techniques

Since measurements are not dynamic, size distributions from these techniques are different from those obtained by previously described techniques, and careful interpretation is required to avoid confusion. When performed properly, these techniques provide information on size, shape, degree of agglomeration, and other physical properties such as density and composition.

Sedimentation and Elutriation

These techniques are suitable for particles in the 1 to 100 μm size range. In this size range, particle sedimentation velocity is proportional to the square of the particle diameter.

If the aerosol which contains the particles of interest is introduced into a chamber which is then sealed to form a quiescent zone, the particles will immediately begin to settle to the bottom with various velocities. By measuring the rate at which the aerosol concentration changes at various levels, or the rate at which mass accumulates on the bottom, it is possible to calculate a particle size distribution.

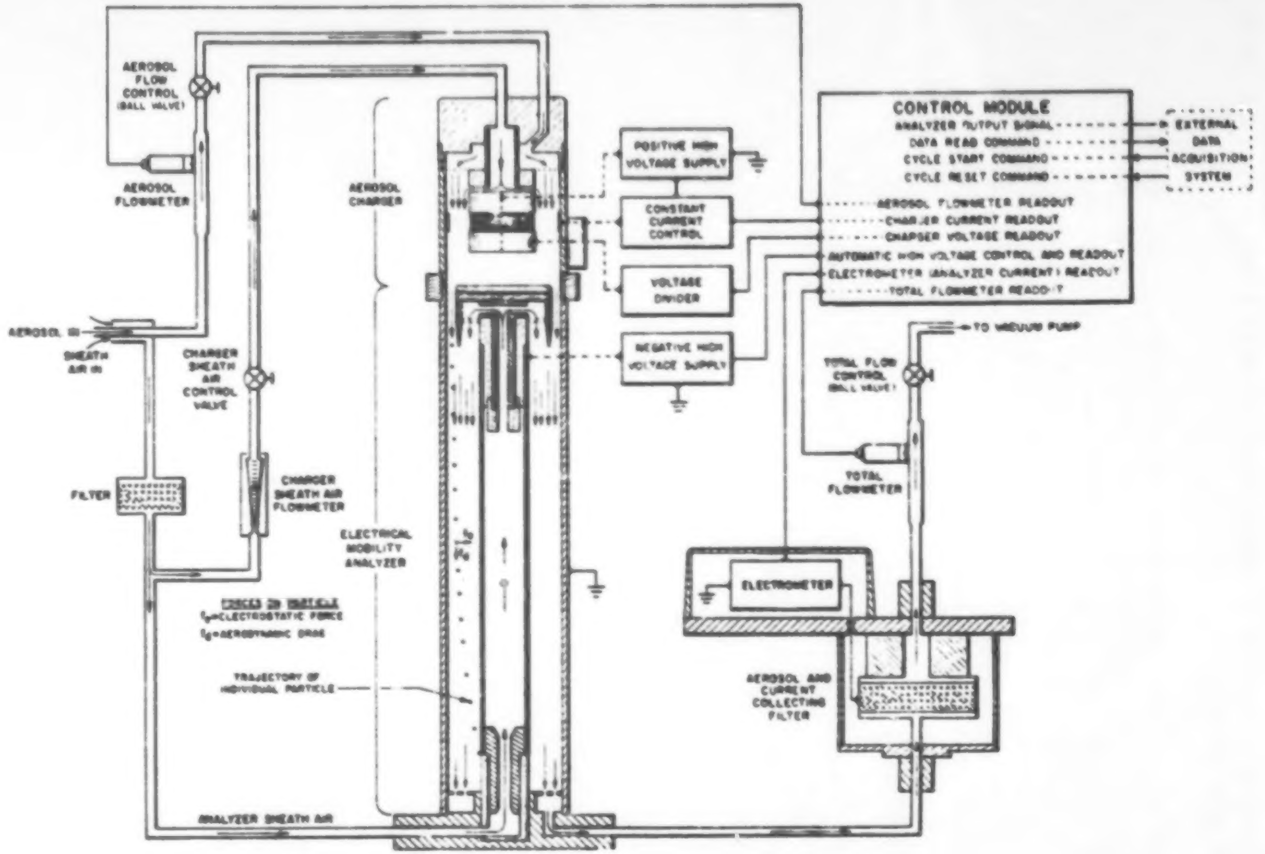

AEROSOL FLOW CONTROL (BALL VALVE)
AEROSOL FLOWMETER
AEROSOL IN
SHEATH AIR IN
CHARGER SHEATH AIR CONTROL VALVE
FILTER
CHARGER SHEATH AIR FLOWMETER
AEROSOL CHARGER
ELECTRICAL MOBILITY ANALYZER
FORCES ON PARTICLE
f_e=ELECTROSTATIC FORCE
f_d=AERODYNAMIC DRAG
TRAJECTORY OF INDIVIDUAL PARTICLE
ANALYZER SHEATH AIR
POSITIVE HIGH VOLTAGE SUPPLY
CONSTANT CURRENT CONTROL
VOLTAGE DIVIDER
NEGATIVE HIGH VOLTAGE SUPPLY
CONTROL MODULE
ANALYZER OUTPUT SIGNAL
DATA READ COMMAND
CYCLE START COMMAND
CYCLE RESET COMMAND
AEROSOL FLOWMETER READOUT
CHARGER CURRENT READOUT
CHARGER VOLTAGE READOUT
AUTOMATIC HIGH VOLTAGE CONTROL AND READOUT
ELECTROMETER (ANALYZER CURRENT) READOUT
TOTAL FLOWMETER READOUT
EXTERNAL DATA ACQUISITION SYSTEM
TO VACUUM PUMP
TOTAL FLOW CONTROL (BALL VALVE)
TOTAL FLOWMETER
ELECTROMETER
AEROSOL AND CURRENT COLLECTING FILTER

Figure B-5. Schematic Diagram of the Electrical Aerosol Analyzer (14)

Sedimentation is particularly well suited for automated readout of the w(t) versus t information which could be done by gravimetric means. Cahn* Instrument Company has available a settling chamber attachment for their electronic microbalance. Vibrating Crystal microbalance sensors could also be utilized to obtain these data.

If the air in the aerosol chamber is not stagnant but moves upward, particles with settling velocities equal to or less than the air velocity will have a net velocity upward, and particles which have settling velocities greater than the air velocity will move downward. This is the principle of "elutriation" which is used frequently to measure the size distribution of dusts. Figure B-6 shows the Roller particle size analyzer which is frequently used for this purpose, and is available commercially.**

Centrifugal Separation

The process of separating particles according to the Stokes diameter can be accomplished more quickly if a strong centripetal acceleration is applied. Figure B-7 shows a commercial centrifugal particle classifier (Bahco) that has been accepted by the ASME and is routinely used to measure the size distribution of powders.

Electrical Conductivity

A very convenient technique for measuring the size distribution of powdersw which can be suspended in an electrolyte dispersing medium is conductivity modulation. A commercially available device, the Coulter Counter, is shown in Figure B-8, a schematic which illustrates the operating principle of the Coulter Counter. Particles suspended in an electrolyte are forced through a small aperture in which an electric current has been established. Each particle displaces electrolyte in the aperture, providing an electrical pulse which is proportional to the particle electrolyte interface volume. A special pulse height analyzer is included with the system which allows convenient data acquisition. A bibliography of publications related to the operation of the Coulter Counter has been compiled by the manufacturer and is avilable on request.

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* Cahn Instrument Company, 7500 Jefferson Street, Paramount, California 90723.

** The Roller particle size analyzer is available from the American Standard Instrument Company, Inc., Silver Springs, Maryland.

*** Available from Coulter Electronics, Inc., 590 West 20th Street, Hialeah, Flordia 33010.

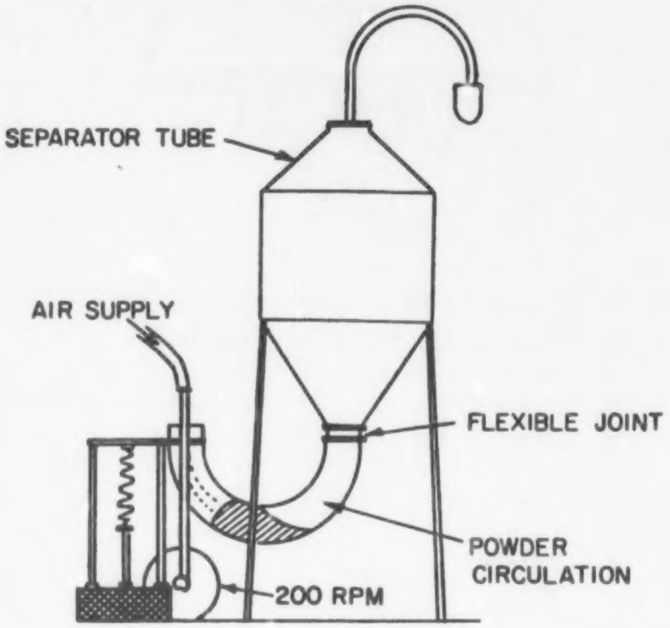
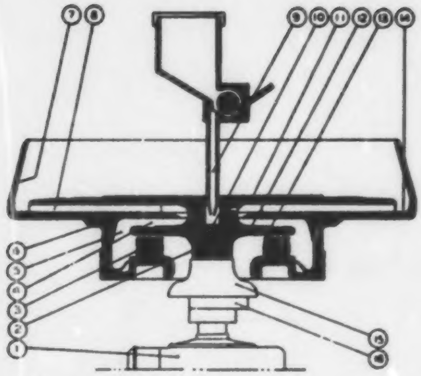

SEPARATOR TUBE
AIR SUPPLY
FLEXIBLE JOINT
POWDER CIRCULATION
200 RPM

Figure B-6. The Roller Elutriator (After Allen) (16)



1. Electric Motor
2. Threaded Spindle
3. Symmetrical Disc
4. Sifting Chm
4. Sifting Chamber
5. Container
6. Housing
7. Top Edge
8. Radial Vanes
9. Feed Point
10. Feed Hole
11. Rotor
12. Rotary Duct
13. Feed Slot
14. Fan Wheel Outlet
15. Grading Member
16. Throttle

Figure B-7. Simplified Schematic Diagram of a Bahco-Type Micro-Particle Classifier Showing Its Major Components (17)

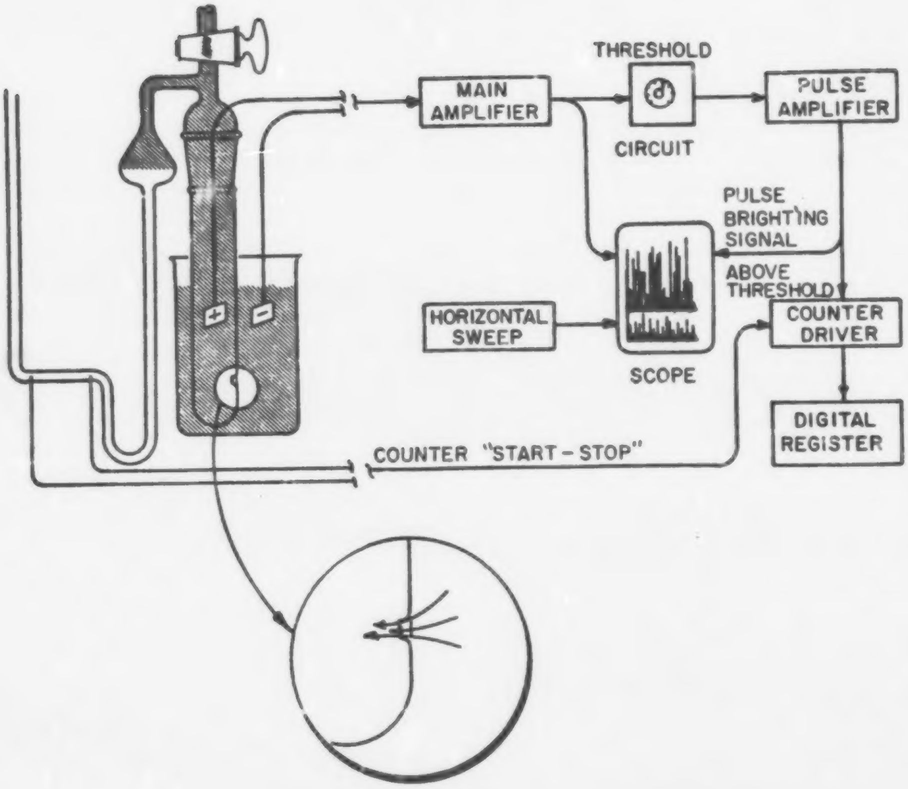

THRESHOLD
MAIN AMPLIFIER
PULSE AMPLIFIER
CIRCUIT
PULSE BRIGHTING SIGNAL
ABOVE THRESHOLD
HORIZONTAL SWEEP
COUNTER DRIVER
SCOPE
DIGITAL REGISTER
COUNTER "START - STOP"

Figure B-8. Operating Principle of the Coulter Counter
Courtesy of Coulter Electronics

Disadvantages with the use of this device are the limited size span which can be covered with any one orifice, the range being limited at the fine end by rapidly declining resolution as the particle volume becomes small compared to the orifice dimensions, and limited on the large end by the physical size of the orifice itself. A secondary problem is obtaining a suitable carrier liquid which has the required conductivity and in which the particle can be dispersed without dissolving.

Microscopy

Cadle (15) has discussed methods of illumination, the selection of optics, sample preparation, and counting techniques which are used in obtaining the best aerosol characterization by means of microscopy. The major technological innovations since Cadle's discussion are the development of the scanning electron microscope and computerized systems which can scan microscopic samples and do the statistical analysis very rapidly. Scanning Electron Microscopes (SEM) are now known to most researchers and have the definite advantage of easier sample preparation and much improved depth of field as compared to transmission type electron microscopes. These devices are unparalleled for convenient studies of surface features, particle shape, agglomeration, and semi-quantitative compositional analysis.

Computerized scanning devices have been developed which can be used with optical microscopes, scanning or transmission electron microscopes, and even photographs to obtain size and shape information on several bases.

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APPENDIX C

HEALTH EFFECTS OF PARTICULATE POLLUTANTS

(The major part of this appendix was abstracted from unpublished information provided by the project officer and from previous work done by MRI on Contract No. CPA 22-69-104)

INTRODUCTION

This appendix reviews the health effects of particulate air pollutants and describes the mechanisms of pollutant uptake, chiefly respiratory, in the human body. In spite of the paucity of epidemiological data concerning specific pollutants, the evidence that is accumulating is sufficient to establish concern. The surprising fact may be not that air pollutants cause serious health effects including death, but that the human body is as resistant as it is to many of these potentially debilitating species. Unfortunately, this latter observation may be attributable to the experimental difficulties in establishing cause and effect relationships, since exposures cannot be accurately measured, sensitivities vary from person to person, and many complex secondary processes produce first-order effects in the interaction.

The following sections of this appendix present (a) a discussion of the general and specific health effects associated with air pollutants, and (b) health effects attributable to particulate pollutants.

GENERAL HEALTH EFFECTS OF AIR POLLUTANTS

Air pollutants and other exogenous chemicals can cause a wide variety of health effects ranging from discomfort to delayed pathological conditions.

Smell, taste, touch, vision, and hearing are well-developed senses in humans, and a pollutant that brings discomfort by way of the senses elicits responses from intricate biological mechanisms. These are, in part, protective mechanisms, and stimulation of them naturally evokes behavioral as well as other reactions.

Mild physical irritation is a common response to exposure to pollutants. A temporary rash, cough, reddening or tearing of the eyes are common responses. Accompanying even quite mild physical irritation is often an increase in respiration rate. in pulse rate, and in blood pressure. Of no consequence to the healthy, this can be dangerous to the weak, the malnourished, the sick, the very young, and the very old, especially after prolonged exposure. For SO_x, total suspended particulates and suspended sulfates in polluted air, one or more of the following effects has been demonstrated: increase in chronic bronchitis, increase in acute lower respiratory disease, aggravation of cardiopulmonary symptoms, and aggravation of asthma. These substances thus probably contribute to mortality for a segment of the human population (those individuals who are sensitive and heavily exposed).

Exposure to relative low concentrations of hazardous industrial materials and products (such as arsenic, asbestos, barium, beryllium, boron, cadmium, chlorine, chromium, copper, cluorine, lead, manganese, mercury, nickel, selenium, tin, vanadium, and zinc) is known to have harmful effects on one ore more of the basic systems of the body, e.g., nervous skeletal, muscular, respiratory, digestive, excretory, and circulatory (1). Severity generally varies with concentration. The less severe effects--for example, headache, labored breathing, pulmonary congestion, dermatitis, chest pain, dizziness, drowsiness, painful joints, fever, perspiration, muscle pain, vomiting, diarrhea, emotional disturbance, speech difficulty, tremors, and constipation--are generally correctable if exposure is stopped in time. If not, failure of one or more systems occurs and death is the result. Severity and type of effect varies with the element, the physical form of the element (solid, liquid, or gas), its presence in different chemical combinations, and the nature of contact (skin contacted, swallowed, or breathed).

Certain elements, when introduced into the body, are sequestered, accumulate, and cause delayed pathological conditions. This may occur as the result of an active mechanism, or it may occur passively (simply because of limited capacity for the body systems to remove it). Cadmium, mercury, asbestos, and lead are among the elements known to accumulate. The danger is insidious in that accumulation may occur so slowly and the effect may be so slight and gradual that, until catastrophic proportions are reached, no obvious harm is noticed. Weakening by general poisoning, with death attributed to other causes, can occur. Failure of renal, respiratory, nervous, or other systems may happen rather abruptly after long but low-level exposure, as the carrying capacity of the body is surpassed (1).

SPECIFIC HEALTH EFFECTS OF AIR POLLUTANTS

Teratogenesis, carcinogenesis, cocarcinogenesis, and mutagenesis are specific health effects associated with air pollutants. Each of these specific effects are briefly discussed next.

TERATOGENESIS

Teratogenesis is defined as the formation of a congenital defect, the resulting abnormalities ranging from biochemical and microscopic to functional and gross morphological. Three groups of human teratogens are recognized--viruses, radiation, and chemical (including drugs). Mercurials are one class of chemicals that have been found to be teratogenic (2). The possibility exists that many air pollutants may be teratogenic, but little testing has yet been done on specific air pollutants. Also lacking are experimental data on the tertogenicity of compounds administered by way of the respiratory route in general (2).

Certain chemicals that enter the atmosphere via industry have been determined to be teratogenic in experimental mammals. These include nitrous oxide, urethane, benzene, dimethylsulfoxide, propylene glycol, and certain compounds of Hg, Pb, As, Li, and Cd (3). All pesticides are suspected teratogens since they are specifically selected for their antagonism to growth and metabolism. Those pesticides tested and found to be teratogenic are 2, 4, 5-T, carboryl, captan, and folpet. However, whether or not any agent placed in the atmosphere by human activity is present in sufficient concentration so as to increase the frequency of occurrence of teratogenic effects beyond the natural (spontaneous) frequency is largely an open question (3).

CARCINOGENESIS AND COCARCINOGENESIS

Carcinogenesis if the formation of malignant neoplasm, typically an invasive growth capable of metastasis and often ending in illness and death. Mutation is one theory which has been proposed as a mechanism to explain carcinogenic action, i.e., mutation in somatic cells. Other possible mechanisms are quasi-permanent and heritable changes in the expression of genes rather than in the genes themselves, activation of latent viruses, and selective pressures in the body (e.g., immunological factors) which allow abnormal cells (latent presumptive tumor cells) to grow and multiply. All four possibilities are plausible explanations (4).

There is reason to believe that all chemical carcinogens are strong electroph ilic agents or are converted to such in the body. Several metal ions are electrophilic and have been shown to have carcinogenic activity. These include Be^{++}, Ca^{++}, Pb^{++}, and Ni^{++} (6).

There are many examples of correlation between incidence of cancer and occupation, which indicate possible cause for concern for many pollutants. Workers exposed to mustard gas, chromium compounds, arsenic, nickel, beryllium, asbestos, radiation, and a variety of hydrocarbons have been shown to have (but not conclusively in every case) some increased frequency of cancer (5).

MUTAGENESIS

Mutagenesis is the formation of an altered gene or chromosome. Mutagenic alterations, therefore, may give rise to hereditary changes in plants and animals. Such changes can be produced by air. A wide range of compounds have been found to be mutagenic (6-8). Industrial effluents such as polycyclic organic matter, alkylating agents, metal fumes, etc., should be viewed as potential sources of mutagenic hazard. All mutagenic agents in the environment are particularly alarming since defects produced in offspring are transmitted to successive generations, regardless of elimination of the source of mutagenic agent.

HEALTH EFFECTS ATTRIBUTABLE TO PARTICULATE POLLUTANTS

The effects on man and his environment of particulate matter are produced by a combination of particulate and gaseous pollutants. The effects on human health are, for the most part, related to injury to the surfaces of the respiratory system. Such injury may be permanent or temporary. It may be confined to the surface, or it may extend beyond, sometimes producing functional or other alterations. Particulate material in the respiratory tract may produce injury itself, or it may act in conjunction with gases, altering their sites or their modes of action. A combination of particulates and gases may produce an effect that is greater than the sum of the effects caused by either individually (i.e., synergistic effect).

Laboratory studies of man and other animals show clearly that the deposition, clearance, and retention of inhaled particles is a very complex process, which is only beginning to be understood. Particles cleared from the respiratory tract may exert effects elsewhere. Available data from laboratory experiments do not provide suitable quantitative relationships for establishing air quality criteria for particulates. These studies do, however, provide valuable information on some of the bio-environmental relationships that may be involved in the effects of particulate air pollution on human health.

The following sections present an overview of (a) the physics and physiology of deposition, retention, and clearance in the respiratory system; (b) toxicological studies of atmospheric particulate matter; and (c) epidemiological studies of atmospheric particulate matter.

DEPOSITION, RETENTION, AND CLEARANCE PROCESSES IN THE RESPIRATORY SYSTEM

An understanding of the effect on human health of particulate pollutants requires knowledge of the following processes:

1. Mechanisms and efficiencies of particle deposition in the respiratory system.

2. Retention mechanisms.

3. Clearance mechanisms.

4. Secondary relocation to other sites in the body.

Theoretical and experimental studies have been conducted to define the factors involved in deposition, retention and clearance processes. The principal results of these studies are summarized in the following sections.

Deposition

Theoretical Aspects--

The physical forces which operate to bring about aerosol deposition within the respiratory system vary in magnitude not only with particle size but also with the air velocities and times of transit of the air from place to place within the system and from moment to moment throughout the breathing cycle. Three mechanisms are of importance in the deposition of particulate matter in the respiratory tract:

1. Inertial impaction - greatest importance in deposition of large particles of high density, and at points in the respiratory system where the direction of flow changes at branching points in the airways.

2. Gravitational settling (sedimentation) - most important in the deposition of large particles or of high-density particles such as dusts of heavy metals.

3. Diffusion (Brownian motion) - major mechanism for the deposition of small particles (below 0.1 μ) in the lower pulmonary tract.

The effectiveness with which the decomposition forces remove particles from the air at various sites depends upon the obstruction encountered, changes in direction of air flow, and the magnitude of particle displacement necessary to remove them from the air stream. The anatomical arrangement and physical dimensions of the respiratory system, transport mechanisms, flow rates and gas mixing, and aerosol particle size are important factors that must be considered in any physical analysis of the deposition of inhaled aerosols.

The Task Group on Lung Dynamics has developed a model for the deposition of particles in the respiratory tract (9). Findeisen's anatomical model (10) was chosen as the basis for the Task Group Model. The Task Group used the conventional division of the respiratory tract into three compartments (nasopharyngeal, tracheo-bronchial, and pulmonary), and made three fundamental assumptions in the development of their model. There were: (9)

1. Log-normal frequency distribution is generally applicable to particle sizes in the atmosphere.

2. The physical activity of the individual affects deposition primarily by its action on ventilation.

3. The aerodynamic properties of the particle, the physiology of respiration, and the anatomy of the respiratory tract provide a basis for a meaningful and reliable deposition model.

The primary conclusions from analysis of aerosol deposition based on the above three forces and assumptions are:

1. Aerosols larger than 10 μm are removed in the nasapharyngeal region by inertial impaction.

2. Aerosols of size less than 10 μm deposit in the respiratory tract.

3. Aerosols smaller than 3 μm penetrate deeply into the pulmonary regions gions of the lung.

These boundaries are fuzzy, and deposition curves for aerosols as a function of mean diameter generally are assumed similar to those illustrated in Figure C-1 (11). The predicted deposition curves generally match the observed dependence of deposition on size. Other factors such as breathing rates and aerosol hydroscopicity alter the curves somewhat, but the major features remain.

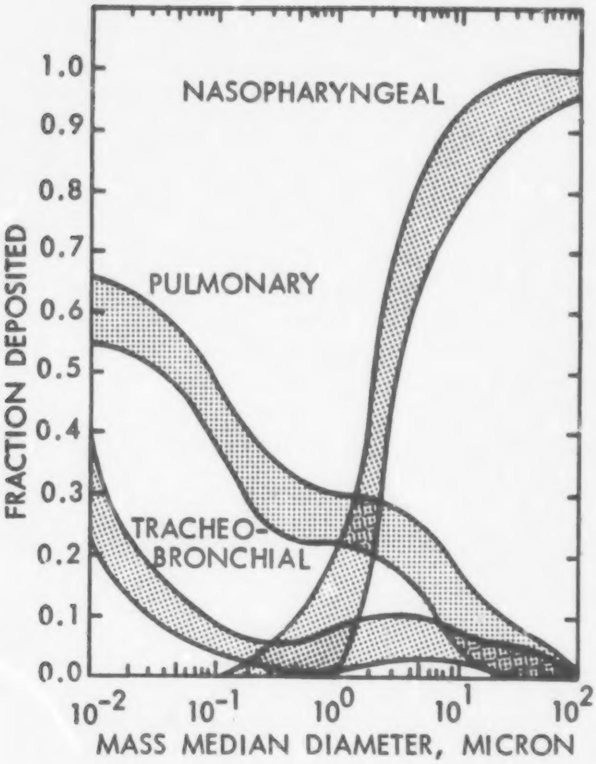

Figure C-1. Fraction of Particles Deposited in the Three Respiratory Tract Compartments as a Function of Particle Diameter

Clearance Mechanisms--

In evaluating the health effects of inspired aerosols, the rapidity and degree to which the aerosols are removed from the lungs play a more significant role than does the magnitude of initial deposition (12). For example, South African gold miners estimated to have inhaled over 1,000 g of pulmonary-sized aerosols over a lifetime are found to retain only 20 g of this quantity in their lungs at death (12).

Relative to other factors, the importance of removal from the respiratory system of trapped particulate materials depends on the rate at which the material elicits a pathological or physiological response. The effect of an irritant substance which produces a rapid response may depend more on the amount of initial trapping than on the rate of clearance. On the other hand, materials such as carcinogens, which may produce a harmful effect only after long periods of exposure, may exhibit activity only if the relative rates of clearance and deposition are such that a sufficient concentration of material remains in the body long enough to cause pathological change. In such a case, the amount of initial deposition will be of relatively minor importance (13).

Different clearance mechanisms operate in the different portions of the respiratory tract, so that the rate of clearance of a particle will depend not only on its physical and chemical properties such as shape and size, but also on the site of initial deposition. The fast phases of the lung clearance mechanisms are different in ciliated and nonciliated regions. In ciliated regions, a flow of mucus transports the particles to the entrance of the gastrointestinal tract, while in the nonciliated pulmonary region, phagocytosis by macrophages can transfer particles to the ciliated region. The rate of clearance is an important factor in determining toxic responses, especially for slow-acting toxicants such as carcinogens. The presence of a nonparticulate irritant or the coexistence of a disease state in the lungs may interfere with the efficiency of clearance mechanisms and thus prolong the residence time of particulate material in a given area of the respiratory tract. In addition, since the clearance of particles from the respiratory system primarily leads to their entrance into the gastrointestinal system, organs remote from the deposition site may be affected (13).

Toxicological Studies of Atmospheric Particulate Matter

Experimental toxicology develops information on the mode of action of specific pollutants, on the relative potency of pollutants having a similar mode of action, and on the effect of one pollutant on the magnitude of response to another. If man could be used as the experimental subject, experimental toxicology would be the best means of deriving air quality criteria. However, the impossibility of performing experiments using human exposures to varying concentrations of a wide range of compounds precludes this direct approach. A limited amount of intentional human experimentation has been conducted, but most of the data for human toxicology are derived from accidental or occupational exposures.

The use of laboratory animals in toxicological experiments is more straightforward, but the obvious anatomical and metabolic differences between the animals and man require the exercise of caution in applying the results of animal exposures to human health criteria. Furthermore, many of the animal experiments have been conducted at exposure concentrations far in excess of those likely to be found in the atmosphere.

In spite of these limitations, toxicological studies have shown that atmospheric particles may elicit a pathological or physiological response. Three types of responses have been determined:

1. The particle may be intrinsically toxic.

2. The presence of an inert particle in the respiratory tract may interfere with the clearance of other airborne toxic materials.

3. The particle may act as a carrier of toxic material.

Few common atmospheric particulate pollutants appear to be intrinsically toxic; of these, the most important toxic aerosol is sulfur trioxide (SO_3) (either as the free oxide, or hydrated as sulfuric acid--H_2SO_4), which has a high degree of toxicity, at least for the guinea pig. Although silica (from fly ash) is frequently present as a pollutant, atmospheric concentrations are normally too low to lead to silicosis. In recent years, however, concern has been expressed over a number of less common toxic particulate pollutants, including lead, beryllium, and asbestos.

Toxic substances may be adsorbed on the surface of particulate matter, which may then carry the toxic principle into the respiratory system. The presence of carbon or soot as a common particulate pollutant is noteworthy, as carbon is well known as an efficient adsorber of a wide range of organic and inorganic compounds.

The role played by the affinity for the adsorbate by the particle is complex. A high affinity will mean that relatively large loads of adsorbate may be carried by each particle. If the adsorbate in its free state is slowly removed from the air in the respiratory system, then the deposition of particles carrying high concentrations may constitute a greater toxic hazard, especially at the localized deposition points. Whether or not the effect is significant depends on whether the efficiency of the desorption and elution processes is greater or less than that of the clearance process. The chemical nature of both adsorber and adsorbate, and the size of the adsorbing particle, all play a part in determining these various efficiencies, and each system will show its own individual characteristics.

Toxicological Studies of Specific Particulate Materials

Certain particulate materials are pulmonary irritants, and have been shown to produce alterations in the mechanical behavior of the lungs; the alteration is predominantly an increase in flow resistance. This was demonstrated by Amdur for sulfuric acid (14), and by Amdur and Corn (15) for ammonium sulfate, zinc sulfate, and zinc ammonium sulfate, using the guinea pig as an assay animal. Nader and co-workers report a correlation between the alterations in pulmonary mechanics and actual anatomical change in cats exposed to aerosols of histamine and zinc ammonium sulfate (16).

The effect of various aerosols on the response to SO_2 has also been examined, using the guinea pig bioassay system. These data are presented in detail in Ref 17. Conditions which lead to the solution of SO_2 in a droplet and catalyze its oxidation can alter the irritant potency of levels of SO_2 which occur in areas of high pollution. The concentration of the catalytic aerosols (soluble salts of iron, manganese, and vanadium) was of the order of 1 mg/m^3 which is higher than concentrations reported for these metals in urban air. Particles which do not form liquid droplets, i.e., nonsoluble salts such as iron oxide fume, carbon fly ash, open hearth dust, and manganese dioxide, did not show a potentiating effect.

Dautrebande and DuBois have reported constriction and increased airway resistance in isolated guinea pig lungs and in human subjects with a wide variety of supposedly inert particulates (18). The relationship of their results to Amdur's work is not clear since Dautrebande's particle concentrations appear to be abnormally high.

When a substance is dispersed in the air in the form of particulate matter, a simple statement of its concentration is insufficient to define in meaningful terms its toxic potential. The size of the particles is also a prime factor in the overall biological impact of inhaled particulate material. This point can be illustrated with data obtained by Amdur and Corn for an aerosol of zinc ammonium sulfate (15). The investigation of this compound was undertaken because it had been identified as one of the substances present during the 1948 Donora fog (19). Figure C-2 shows the response of guinea pigs to zinc ammonium sulfate at a constant concentration (about 1 mg/m^3), but of different particle sizes. Within the size range studied, the irritant potency increased with decreasing particle size. Figure C-3 shows the more extensive data obtained on the dose-response curves of zinc ammonium sulfate at different particle sizes. These data show that not only is the irritant effect greater for the smaller particles at a given concentration, but also the dose-response curve steepens as the particle size is decreased. Thus, if an irritant aerosol is composed of very small particles, a relatively slight increase in its concentration can produce a relatively great increase in irritant response.

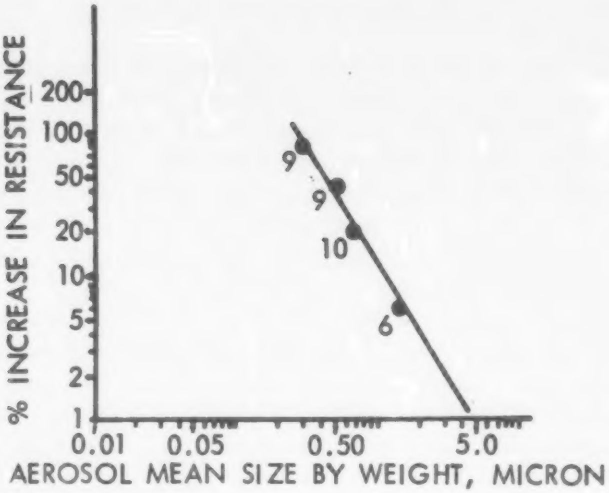

Figure C-2. Effect of Particle Size on the Response to Approximately 1 mg/m^3 Zinc Ammonium Sulfate. Numbers beside each point indicate the number of animals (15)

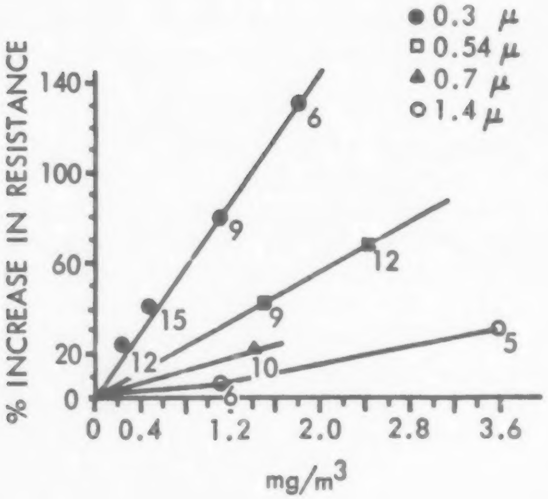

Figure C-3. Relationship of Response to Concentration for Zinc Ammonium Sulfate of Different Particle Sizes. Numbers beside each point indicate the number of animals (15)

From the analytical data (19) it can be estimated that the concentration of zinc ammonium sulfate present during the Donora fog might have been on the order of magnitude of 0.05 to 0.25 mg/m^3. The toxicological data can in no way be extrapolated to predict what, if any, contribution this substance made to the overall irritant character of the atmosphere. On the other hand, the data do indicate that without information on particle size, such predictions are not possible.

The possible influence of inert particulate matter on the toxicity of irritant gases has been the subject of considerable speculation and a limited amount of experimental work. The potentiation of irritant gases by particulate material noted by various investigators has been attributed to the adsorption of gas on the particles. Adsorption of the gas on small particles would tend to carry more gas to the lungs and thus increase the toxicity. Unfortunately, in many of these studies the end point was the dosage required to produce death. With concentrations of this magnitude, the results have little applicability to air pollution.

Amdur has studied the effect of particulate material on the response to sulfur dioxide using the pulmonary flow resistance technique. None of the aerosols used in the studies produced any effect along (17). From these studies it appears that the major mechanism underlying the potentiation is solubility of sulfur dioxide in a droplet and subsequent catalytic oxidation to sulfuric acid.

Figure C-4 shows the effect of aerosols of sodium chloride, potassium chloride, and ammonium thiocyanate, at concentrations of about 10 mg/m^3, on the response to about 2 ppm sulfur dioxide. All these substances are soluble salts which would absorb water to become liquid droplets at the humidity of the respiratory tract. Sulfur dioxide is increasingly soluble in aqueous solutions of these salts as one goes from sodium chloride, to potassium chloride, to ammonium thiocyanate. The degree of potentiation observed can be related in a reasonable manner to the degree of solubility of sulfur dioxide in the salt solutions.

Figure C-5 shows the results of exposure to about 2 ppm of sulfur dioxide alone and in the presence of another group of aerosols. These aerosols do not take on water to become droplets during transit of the respiratory tract, and have no detectable effect upon the response to sulfur dioxide. The combination of data in Figures C-3 and C-4 suggests that solubility in a droplet plays a role (17).

Figure C-6 shows the dose-response curves to sulfur dioxide along and in the presence of aerosols of soluble salts of manganese, iron, and vanadium. These substances were present at a concentration of about 1 mg/m^3.

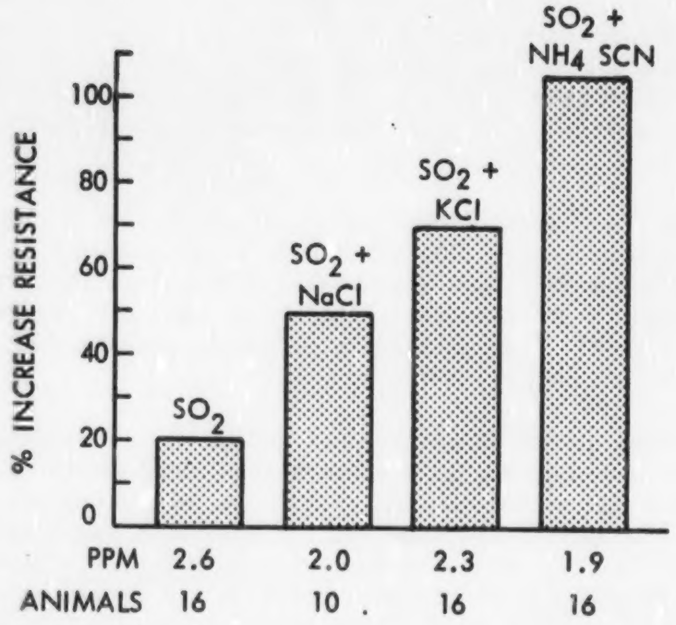

Figure C-4. Effect of Aerosols Capable of Dissolving Differing Amounts of Sulfur Dioxide on the Irritant Potency of the Gas(16)

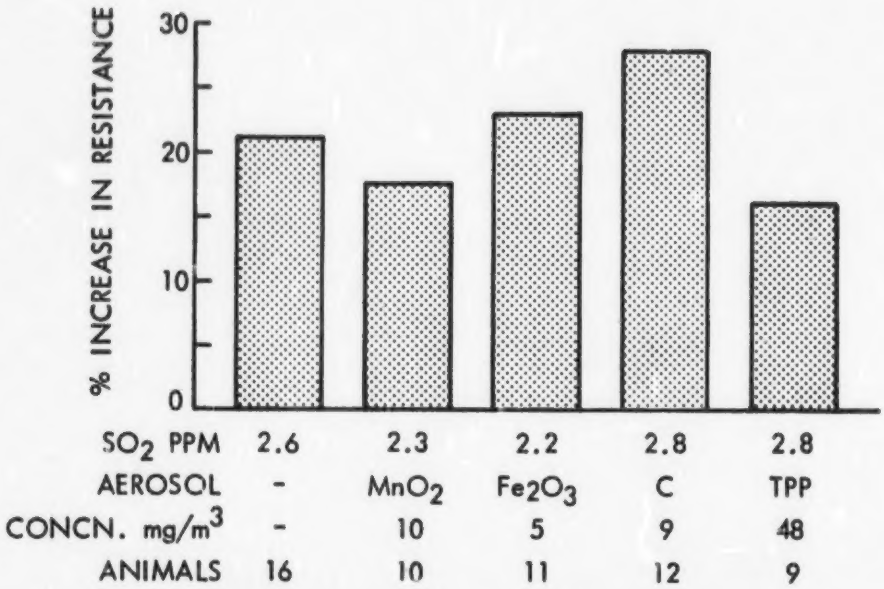

Figure C-5. Response to Sulfur Dioxide Alone and in the Presence of Various Solid Aerosols (16)

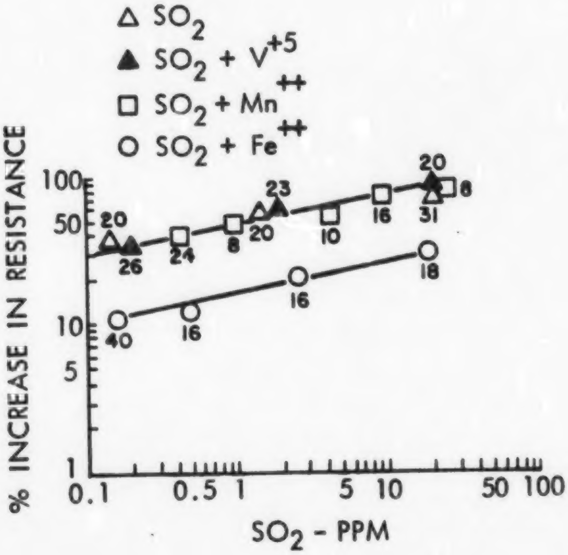

Figure C-6. Effect of Aerosols Which Would Form Droplets and Also Catalyze the Oxidation of Sulfur Dioxide to Sulfuric Acid on the Irritant Potency of the Gas. The Numbers Beside Each Point Indicate the Number of Animals (16)

They have another property in common. When such salts become nuclei of fog droplets, they are capable of catalyzing the oxidation of sulfur dioxide to sulfuric acid (20). The addition of these inert particles produced about a three-fold potentiation in the response to sulfur dioxide. The similar magnitude of potentiation produced by the three salts suggests a similar mechanism for the potentiation. The data from Figure C-4 showing the lack of potentiation by dry manganese dioxide or iron oxide would appear to indicate the importance of solubility.

Experimental data on the effect of particulate matter on the responses to sulfur dioxide in human subjects are very limited. Furthermore, there is no general agreement regarding potentiation by particulates. To date human exposures have been disappointing is disclosing mechanisms of interaction between various air pollutants. On the other hand, there is no evidence as yet for a species difference between animals and man; therefore, we may extrapolate judiciously to man from the animal studies.

CONCLUSIONS

1. Particulate matter may exert a toxic effect via one or more of three mechanisms:

   a. The particle may be intrinsically toxic because of its inherent chemical and/or physical characteristics.

   b. The particle may interfere with one or more of the clearance mechanisms in the respiratory tract.

   c. The particle may act as a carrier of an adsorbed toxic substance.

2. Evaluation of irritant particulates on the basis of mass or concentration alone is not sufficient; data on particle size and number averages per unit volume of carrier gas are needed for adequate interpretation.

3. The toxicological importance to mankind of submicron particles cannot be overemphasized.

4. Particles below 1 μm may have a greater irritant potency than larger particles.

5. A small increase in concentration could produce a greater-than-linear increase in irritant response when the particles are < 1 μm.

6. All particulate matter does not potentiate the response to irritant gases.

7. Both solubility of sulfur dioxide in a droplet and catalytic oxidation to sulfuric acid play a role in the potentiation of sulfur dioxide by certain particulate matter.

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